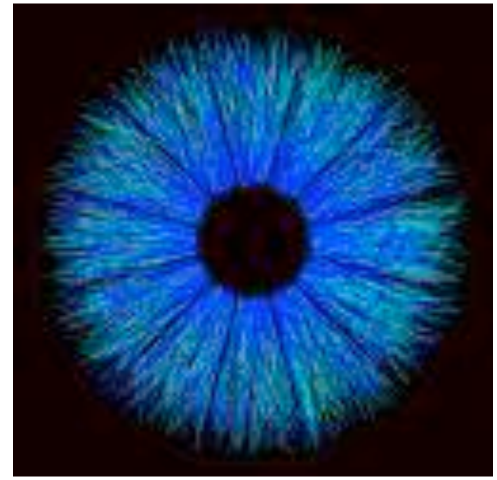
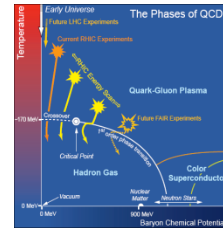


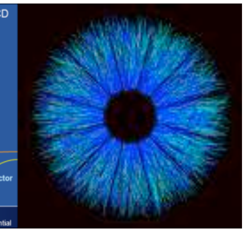
Estimation of QGP shear viscosity based on transverse momentum correlations

Monika Sharma

Wayne State University

Outline

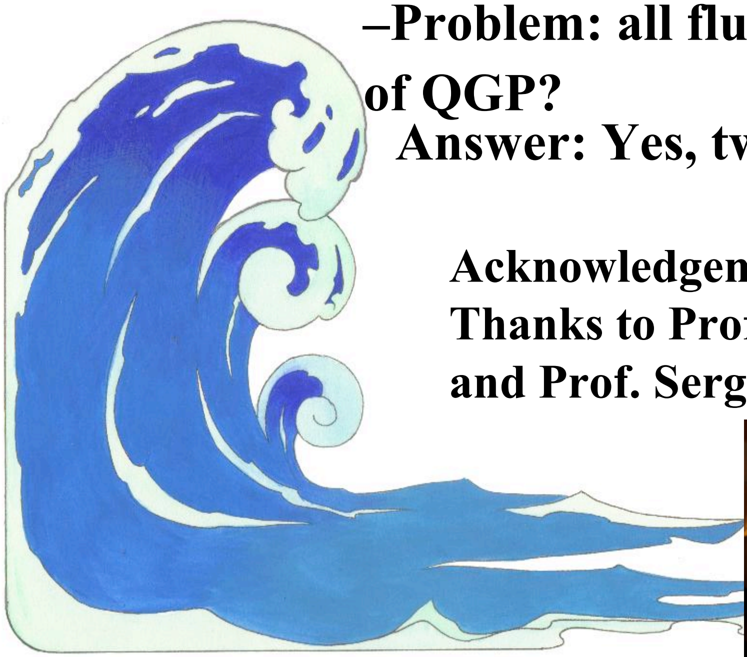




- Selected results from STAR experiment
- Investigating the perfect liquid

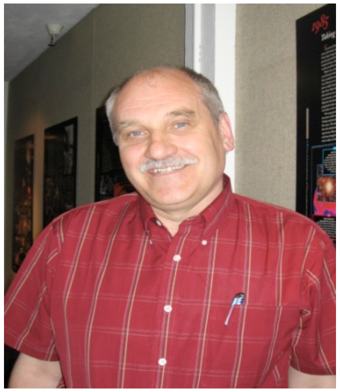
- **Results**
  - **–Problem: all fluids have viscosity, can we measure the viscosity of QGP?**

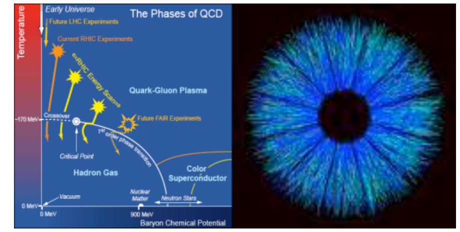
    Answer: Yes, two-particle transverse momentum correlations



Rheology of Quark Gluon Plasma

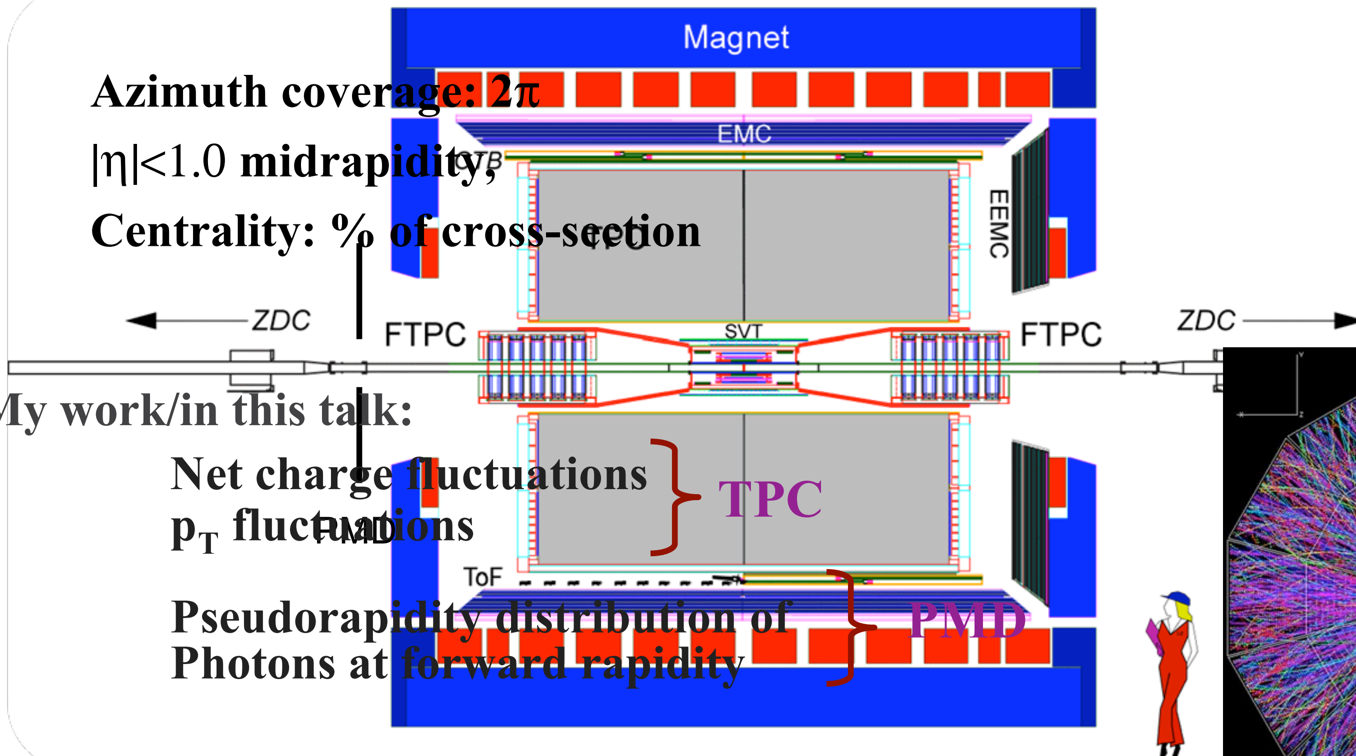
Acknowledgement:
Thanks to Prof. Claude Pruneau, Prof. Sean Gavin and Prof. Sergei Voloshin for many discussions





The STAR experiment

The heart of the experiment: TPC



Azimuth coverage: 2π

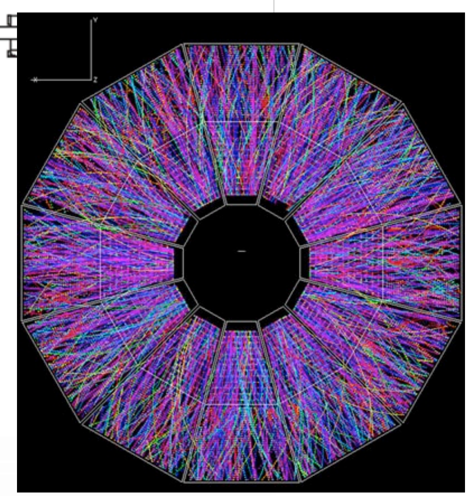
|η|<1.0 **midrapidity**

Centrality: % of cross-section

My work/in this talk:

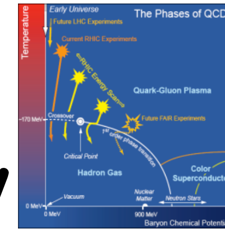
Net charge fluctuations
p_T fluctuations } **TPC**

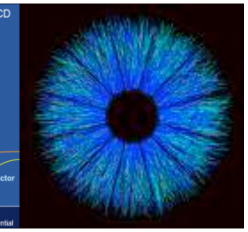
Pseudorapidity distribution of Photons at forward rapidity } **PMD**

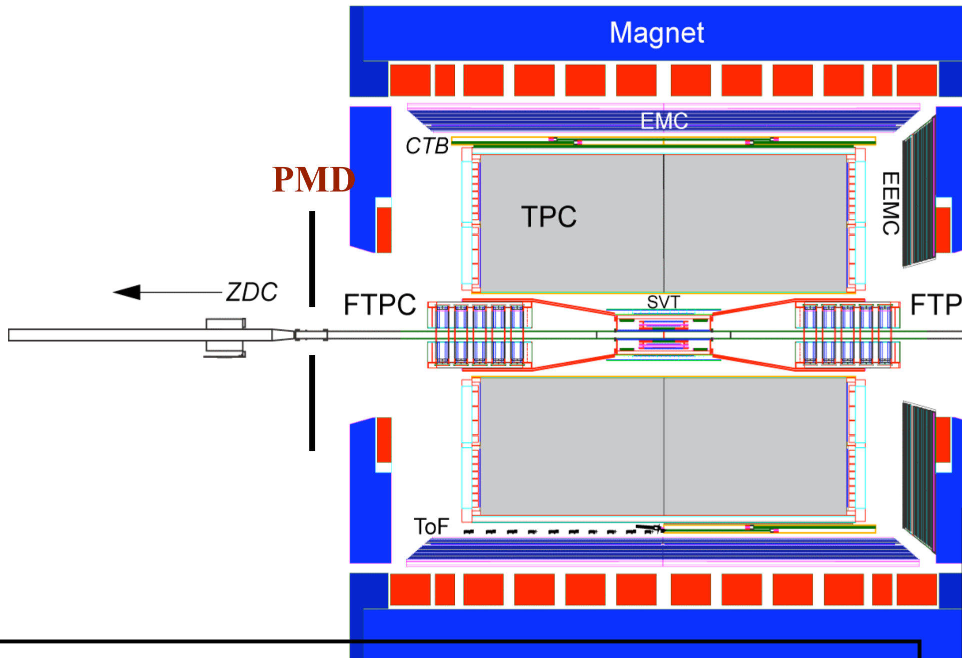


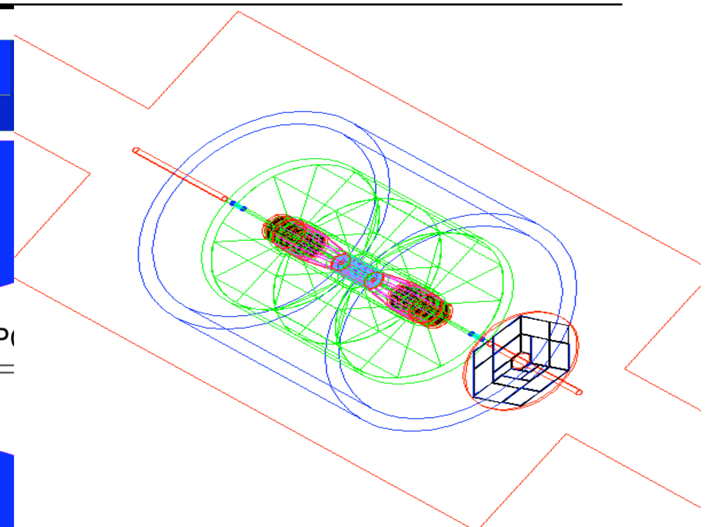
A reconstructed Au+Au collision in the STAR TPC at $\sqrt{s_{NN}} = 130$ GeV

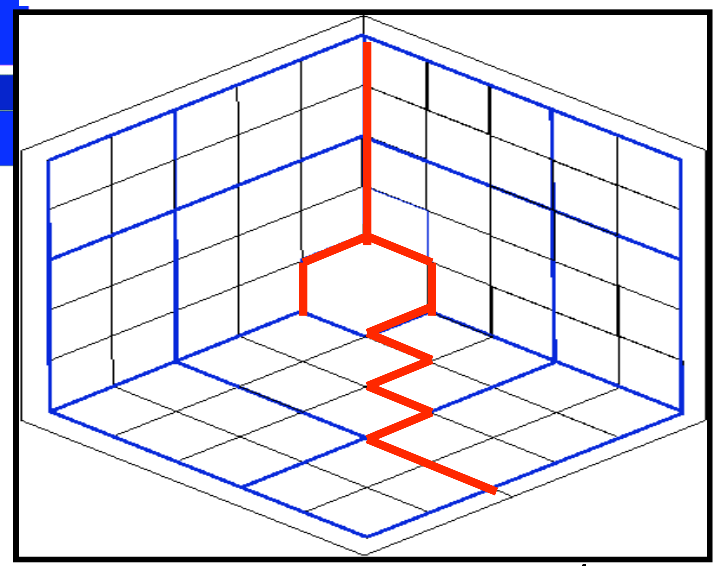
Measurements at forward rapidity





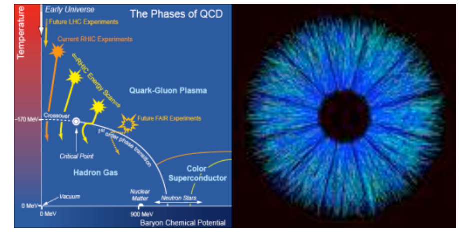






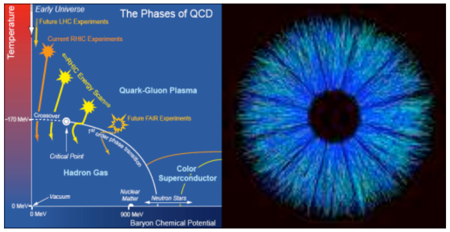
Pre - shower detector with fine granularity

- **Two planes: Veto +Pre-shower**
- **$3X_0$ lead plate**
- **η coverage:** $-3.7 < \eta < -2.3$
- **Distance from vertex : 542 cm**



Motivation

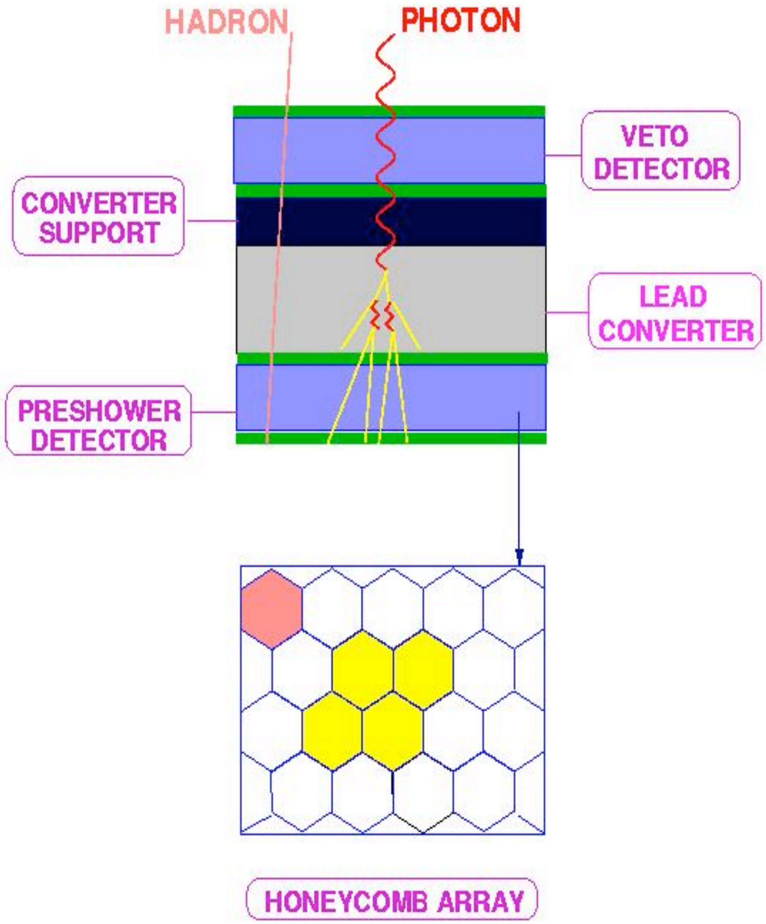
- **Measurements of particle multiplicity provide information on particle production mechanisms.**
  - Ref[1] BRAHMS Collaboration, I. Arsene *et al.,* Nucl. Phys. A 757 (2005) 1;
    PHOBOS Collaboration, B.B. Back *et al.,* Nucl. Phys. A 757 (2005) 28;
    STAR Collaboration, J. Adams *et al.,* Nucl. Phys. A 757 (2005) 102.
    PHENIX Collaboration, K. Adcox *et al.,* Nucl. Phys. A 757 (2005) 184.
- **Event-by-event correlation between photon and charged particle multiplicities can be used to test the predictions of formation of disoriented chiral condensates.**
  - Ref[2] WA98 Collaboration, M.M. Aggarwal *et al.,* Phys. Rev. C 64 (2001) 011901®
- **The variation of particle density in pseudorapidity with collision centrality can shed light on the relative contribution of soft and hard processes in particle production.**
  - Ref[3] PHENIX Collaboration, K. Adcox et al., Phys. Rev. Lett. 86 (2001) 3500.

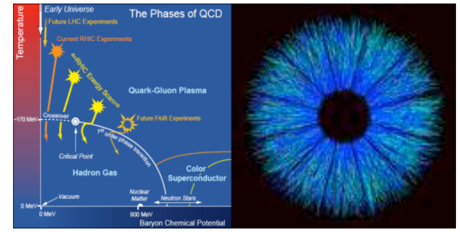


Principle of pre-shower

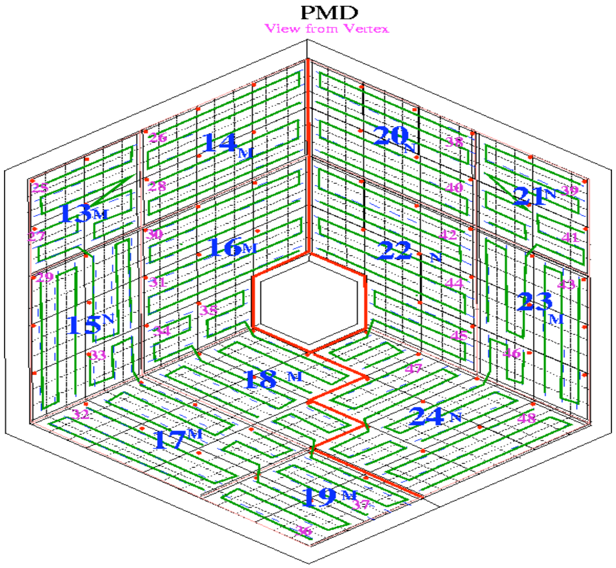
Photon-hadron discrimination

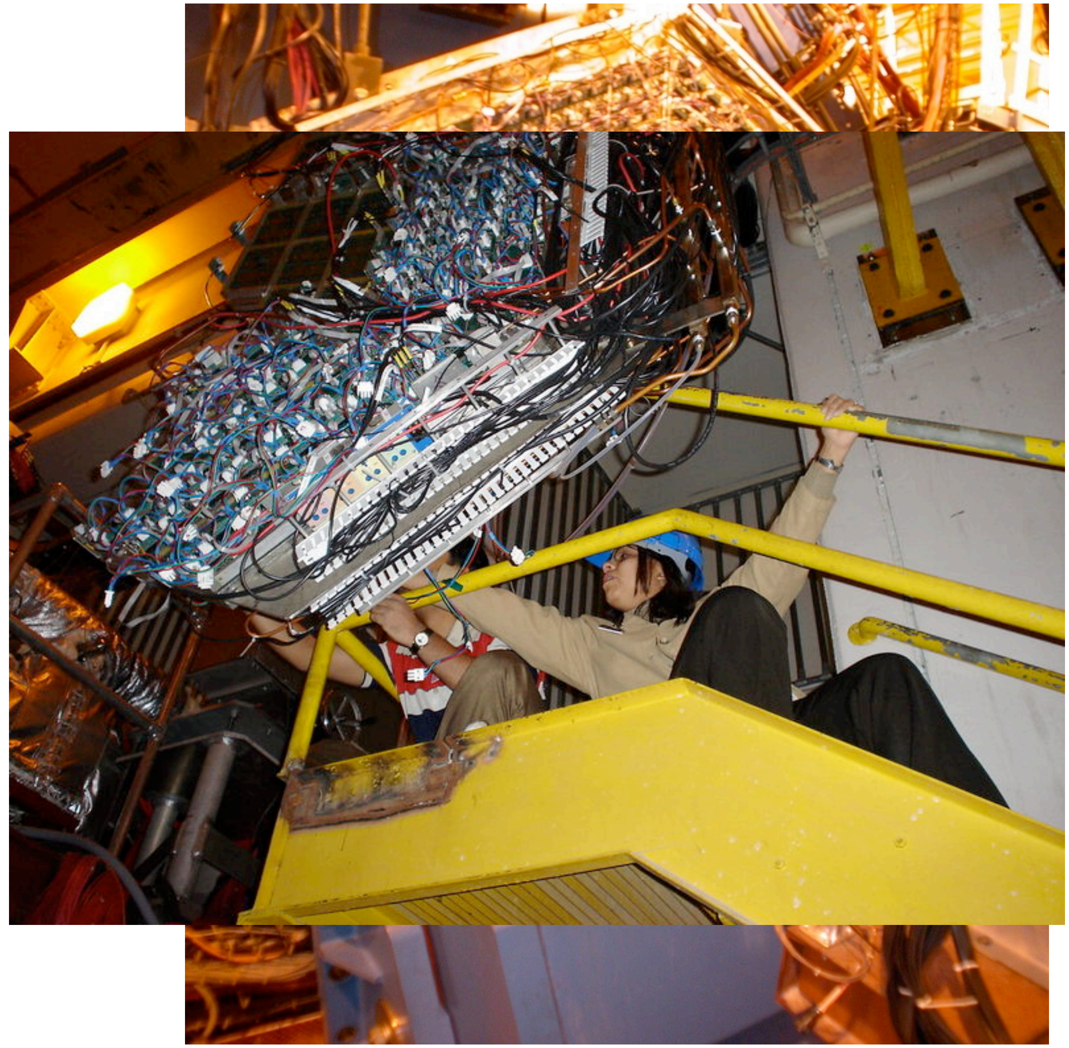
- Photons passing through the converter initiate an electromagnetic shower & produce a large signal on several cells of the sensitive volume of the detector.
- Hadrons normally affect only one cell & produce a signal representing minimum ionizing particles.



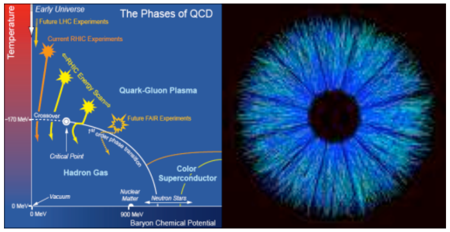


Run configuration



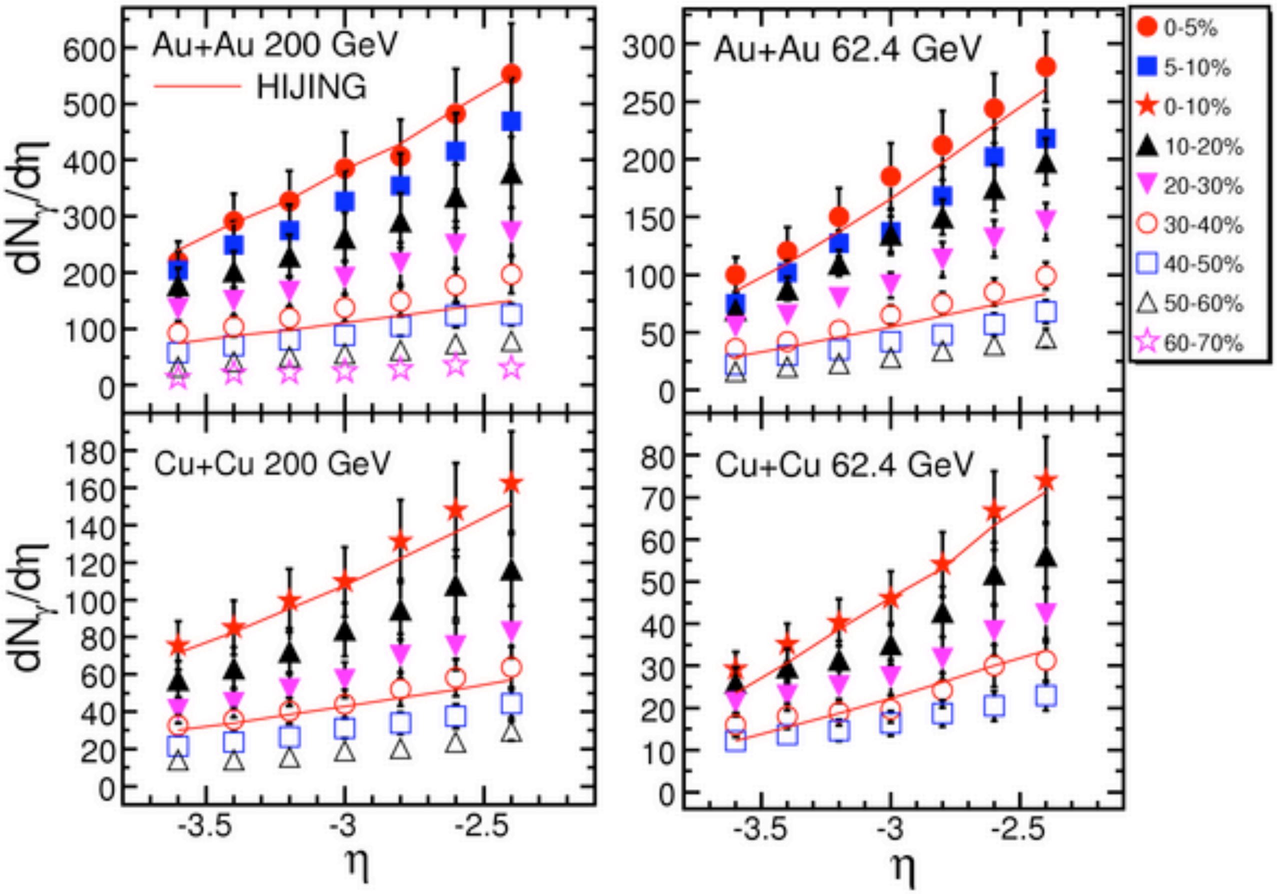


- CuCu 200 GeV, Run V (2005)
- Trigger condition : Minimum bias
- Total number of events analyzed: ~300K

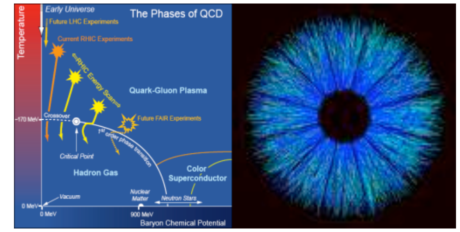


Results - I

B. I. Abelev *et al.*, (STAR Collaboration) Nucl. Phys. A 832 (2009) 134

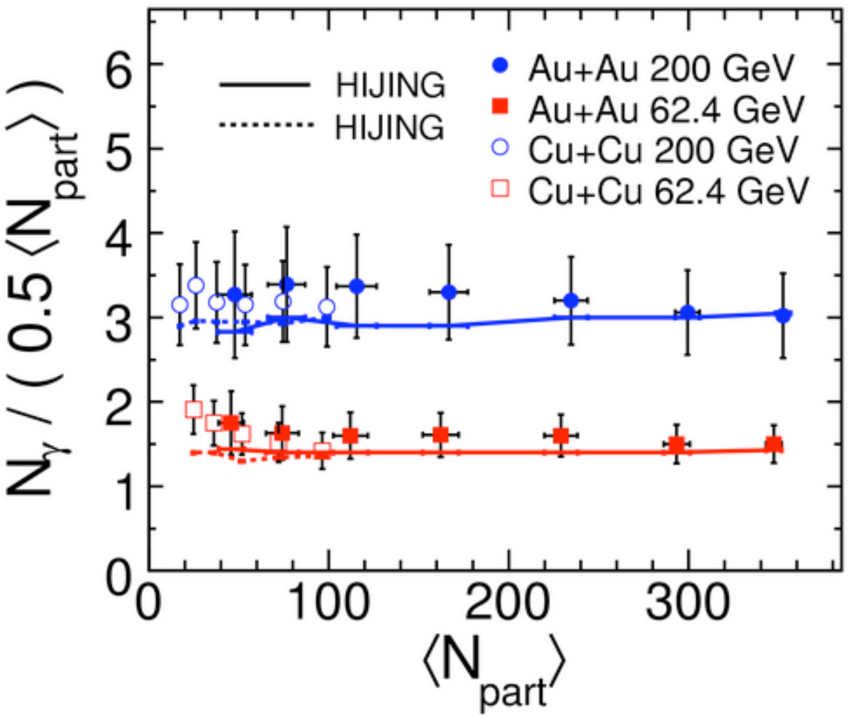


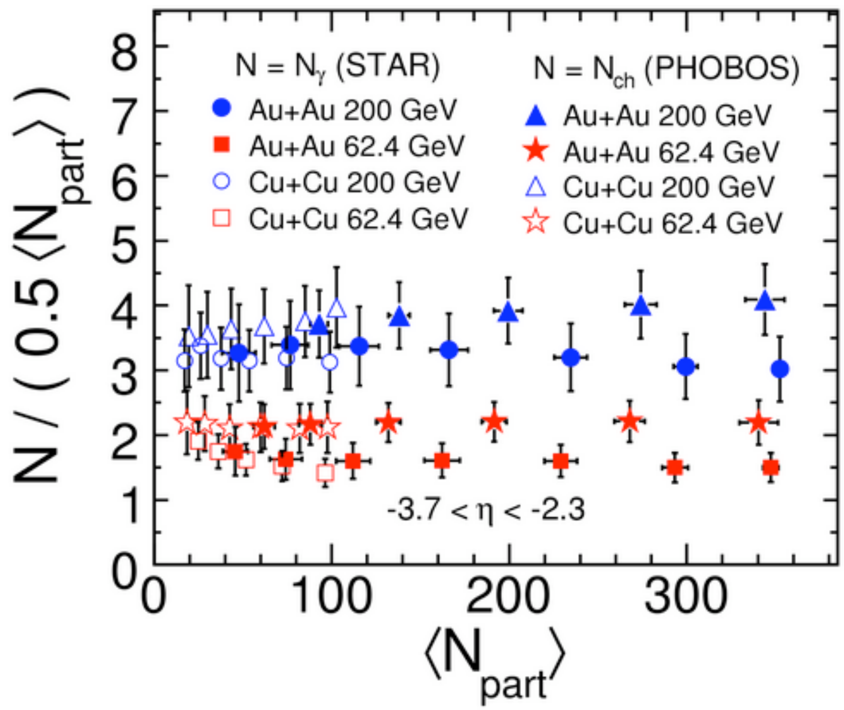
Monika Sharma
Brookhaven National Lab, Mar 30, 2010

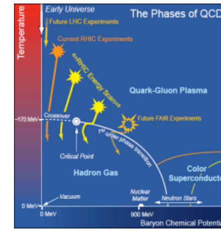


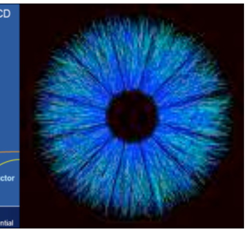
Results - II

B. I. Abelev *et al.*, (STAR Collaboration) Nucl. Phys. A 832 (2009) 134



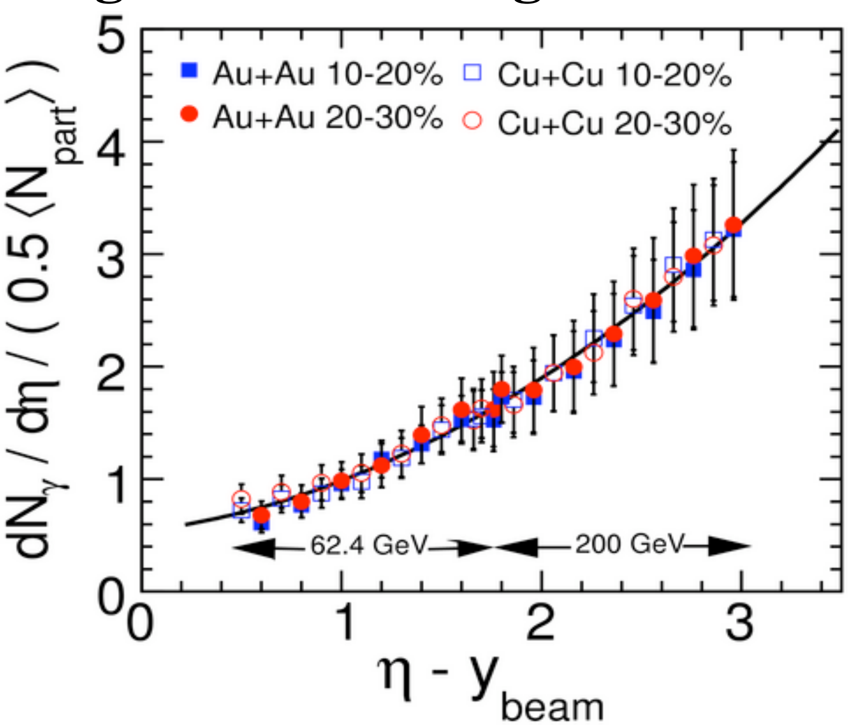


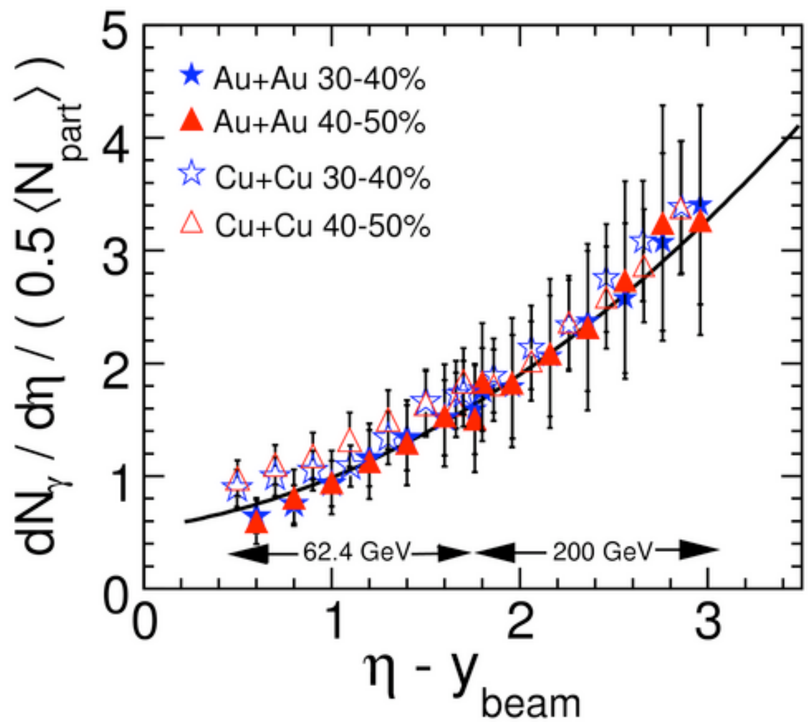




Results - III

Longitudinal scaling

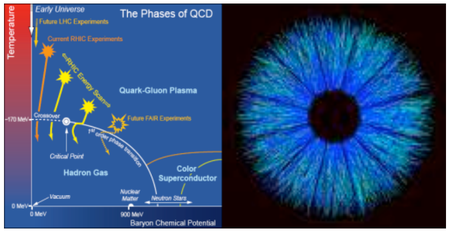




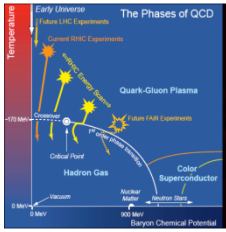
B. I. Abelev *et al.*, (STAR Collaboration) Nucl. Phys. A 832 (2009) 134

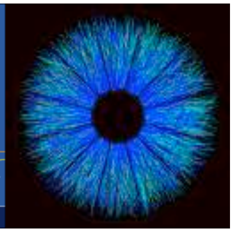
Longitudinal scaling for produced photons is independent of colliding ion species, beam energy and collision centrality

Summary - I



- Presented photon multiplicity distributions measured at forward rapidity $-3.7 < \eta < -2.3$ for Au + Au and Cu + Cu collisions at 200 and 62.4 GeV.
- Photon multiplicity per participating nucleon pair is observed to be independent of collision centrality indicating that photon production is dominated by soft processes.
- Photon production per unit rapidity per average number of participating nucleon pair vs. $\eta - y_{beam}$ shows longitudinal scaling which is independent of beam energy, collision centrality and colliding ion species.





Dynamical net charge fluctuations

- **Quark Gluon Plasma should produce a final state characterized by dramatic reduction of the net charge fluctuations relative to that of a hadron gas.**

$$D = \frac{4\delta Q^2}{\langle N_{ch} \rangle}$$

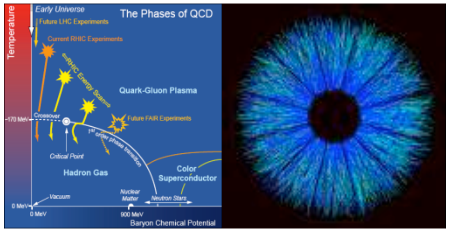
S. Jeon and V. Koch, Phys. Rev. Lett. 85 (2000) 2076

= 1 for quark gluon plasma
= 3 for resonance gas
= 4 for uncorrelated pion gas

- **Net charge correlations/fluctuations are sensitive to the production dynamics :**
  - **Delayed hadronization**
  - **Collective motion**

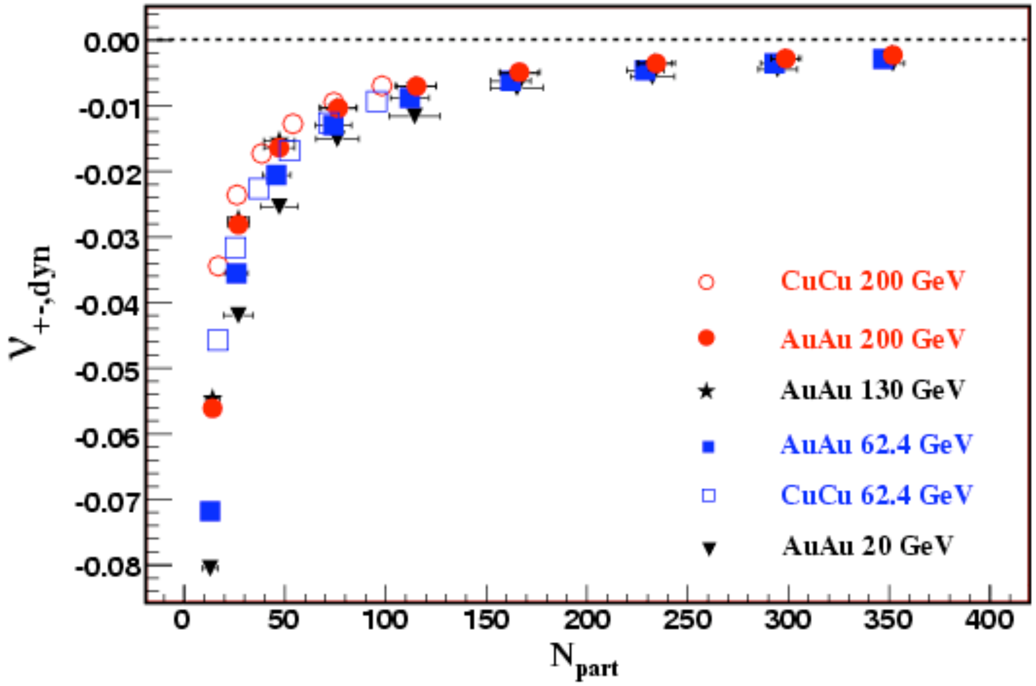
AIM : To study the beam energy and system size dependence of net charge dynamical fluctuations.

Results - I



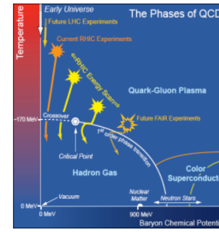
We use net charge dynamical fluctuation measure, $\nu_{\pm,dyn}$

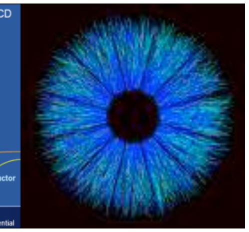
$$\nu_{\pm,dyn} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\times\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$



- **Dynamical net charge fluctuations are finite for both the systems and at all energies.**
- **Weak system size dependence observed here between Au + Au and Cu + Cu systems.**

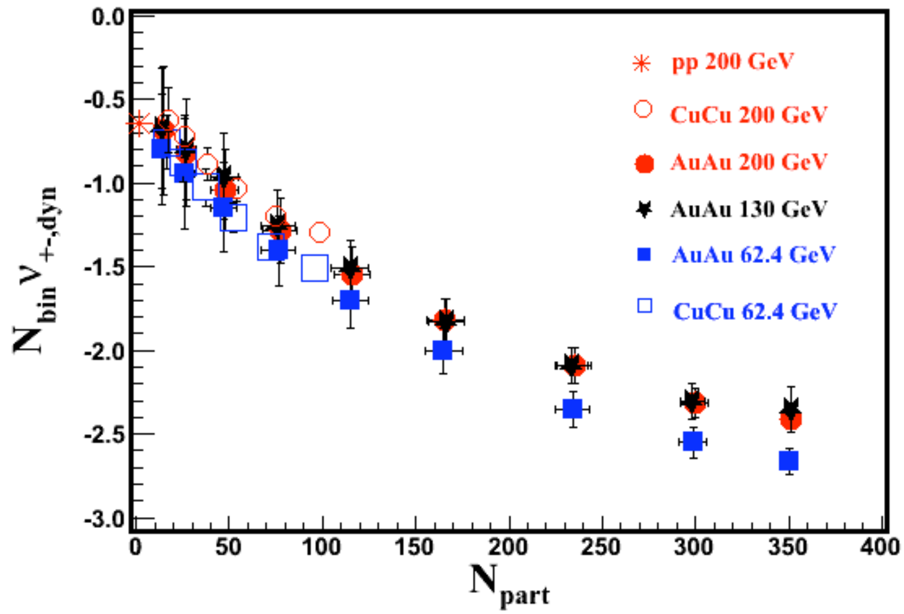
B.I. Abelev *et al.*, (STAR Collaboration) Phys. Rev. C 79 (2009) 024906

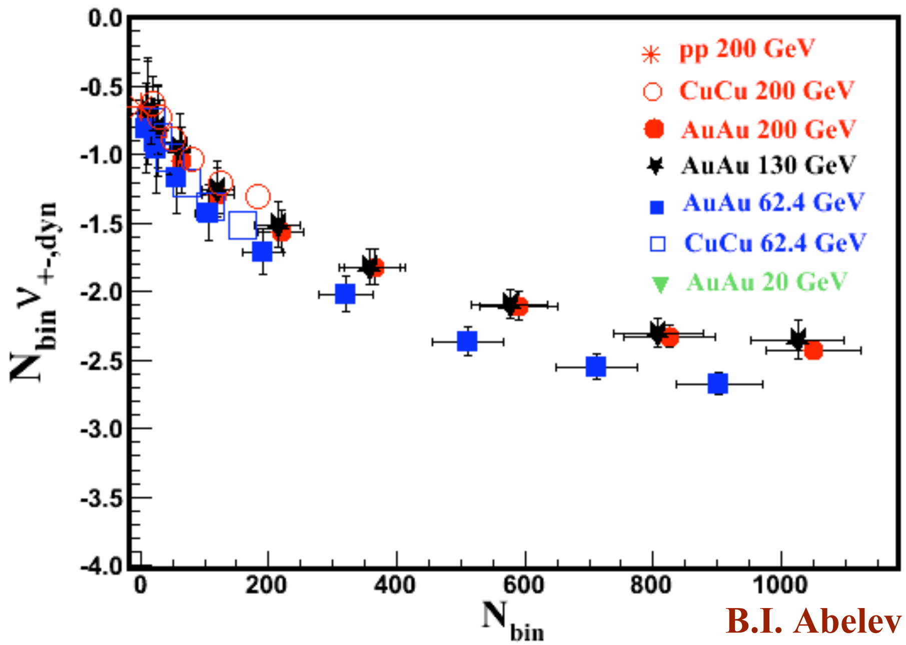




Results - II

- Dataset follow a “common” trend.
- System size dependence still apparent.
- Energy dependence is also observed.
- $\nu_{\pm,dyn}$ does not scale with N binary.



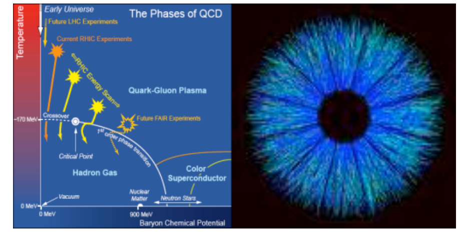


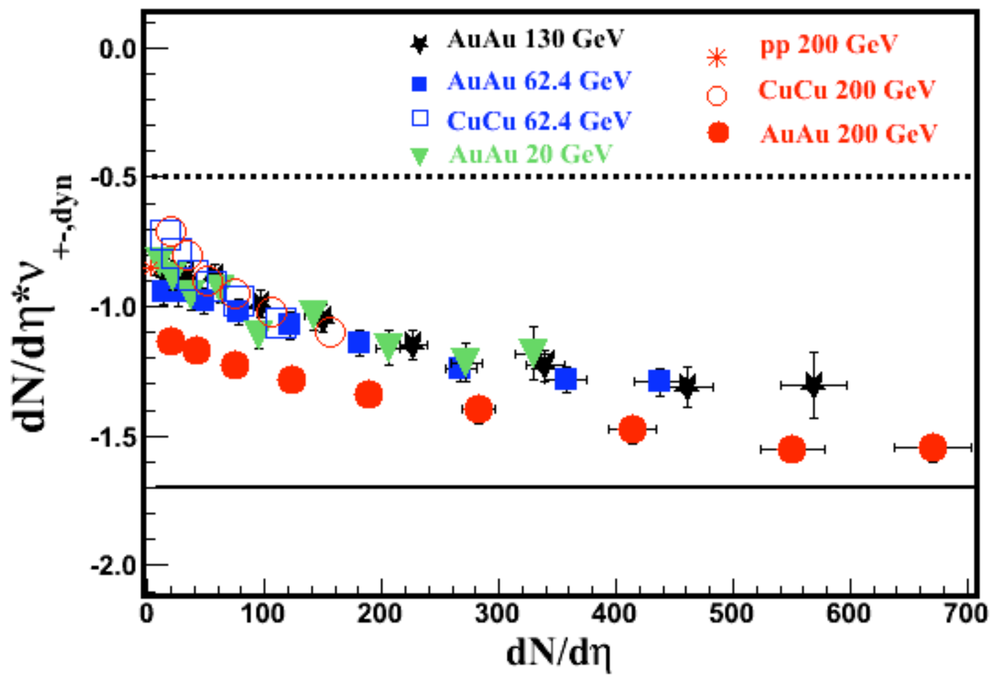
Results extrapolate to pp within errors.

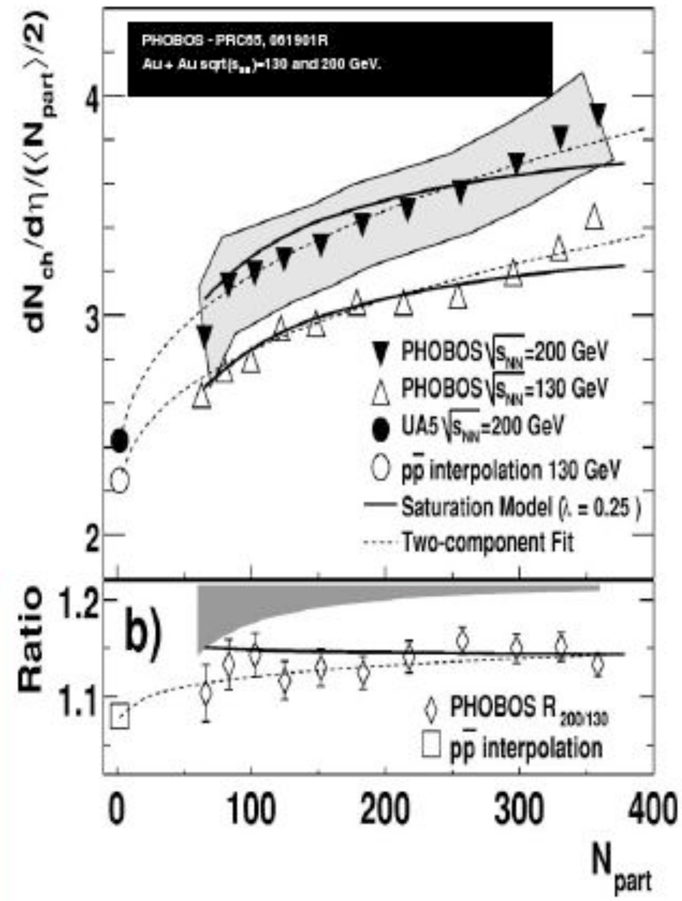
B.I. Abelev *et al.*, (STAR Collaboration) Phys. Rev. C 79 (2009) 024906

B.I. Abelev *et al.*, (STAR Collaboration) Phys. Rev. C 79 (2009) 024906

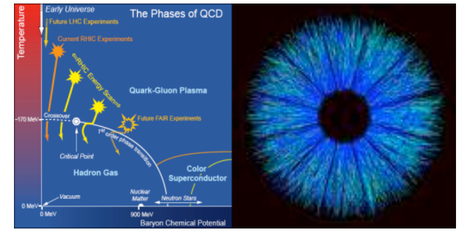
Results - III







- Centrality dependence observed here.
- $dN_{ch}/d\eta/(<N_{part}>/2)$ rises at mid-rapidity by 56% vis-à-vis pp.
- Similar rise (~ 40%) observed here when $\upsilon_{\pm,dyn}$ is scaled with $dN_{ch}/d\eta$.

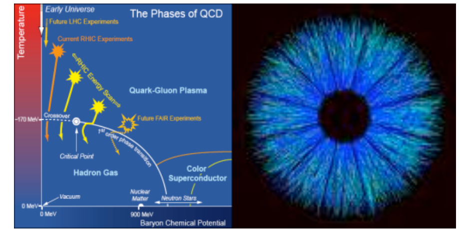


Summary - II

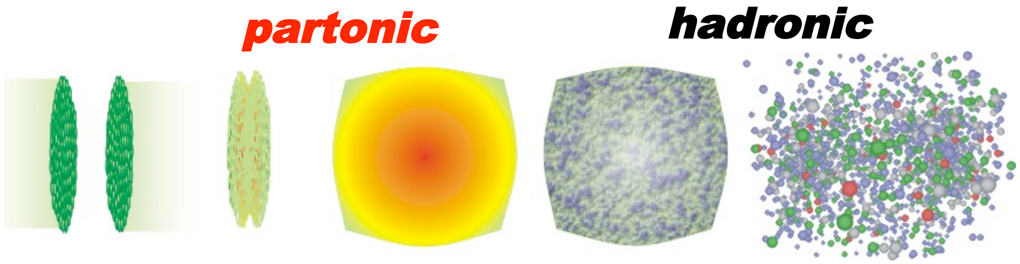
- **Finite dynamical fluctuations observed in both energies & systems measured.**
- **Common behavior – approx. 1/N Vs. centrality.**
- $\dfrac{dN_{ch}}{d\eta} * \vartheta_{\pm,dyn}$ **changes by ~ 40% from peripheral to central**

  collisions as $dN_{ch}/d\eta/(<N_{part}>/2)$ at midrapidity changes by

  almost the same magnitude.



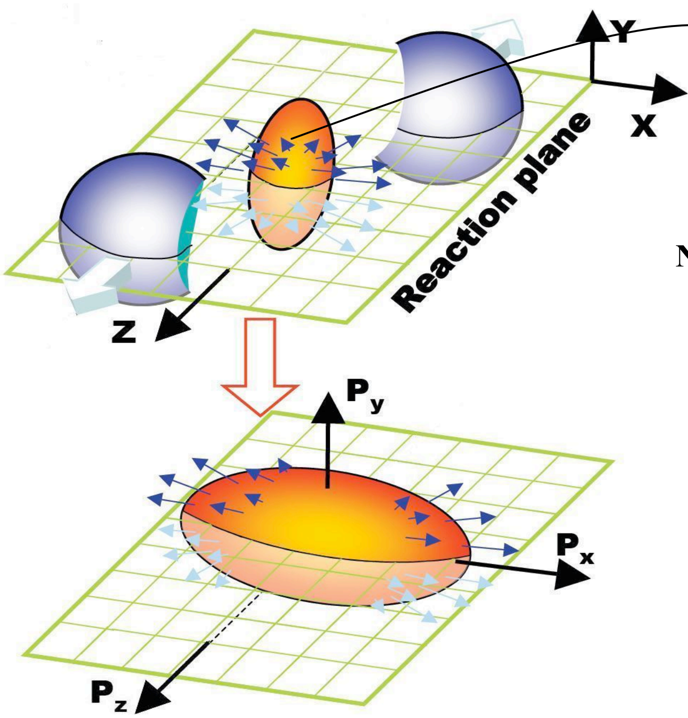
Anisotropic flow



$$\varepsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}$$

Coordinate-Space Anisotropy

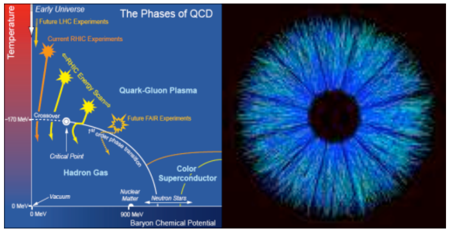
Momentum-Space Anisotropy



Number of participating nucleons

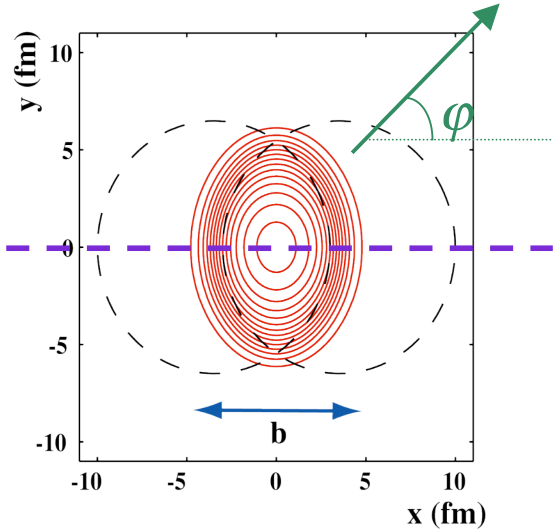
✓Elliptic flow: reveal the early stage collision dynamics

Anisotropic flow.....



Characterize azimuthal dependence of the resulting observables by their Fourier expansion

$$f(\varphi)=\langle f\rangle\left(1+2\sum_n a_n\cos n\varphi+2\sum_n b_n\sin n\varphi\right)$$



With given symmetries and chosen co-ordinate system:

$\varphi=-\varphi$ no sine terms…

$\varphi=\varphi+\pi$ no odd cosine terms…

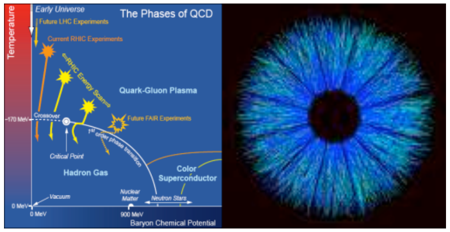
$$\frac{d^3N}{dyp_Tdp_Td\varphi}=\frac{1}{2\pi}\frac{d^2N}{dyp_Tdp_T}\left(1+\sum_{n_i,even}2v_n(p_T)\cos n\varphi\right)$$

$$v_2(p_T)=\langle\cos(2\varphi)\rangle=\frac{1}{dN/dyp_Tdp_T}\int d\varphi\cos(2\varphi)\frac{dN}{dyp_Tdp_Td\varphi}$$

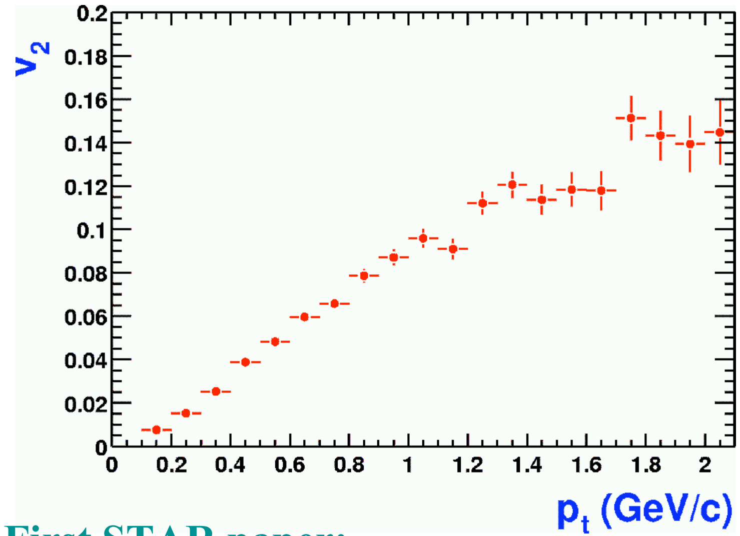
$\downarrow$

Elliptic flow, largest coefficient

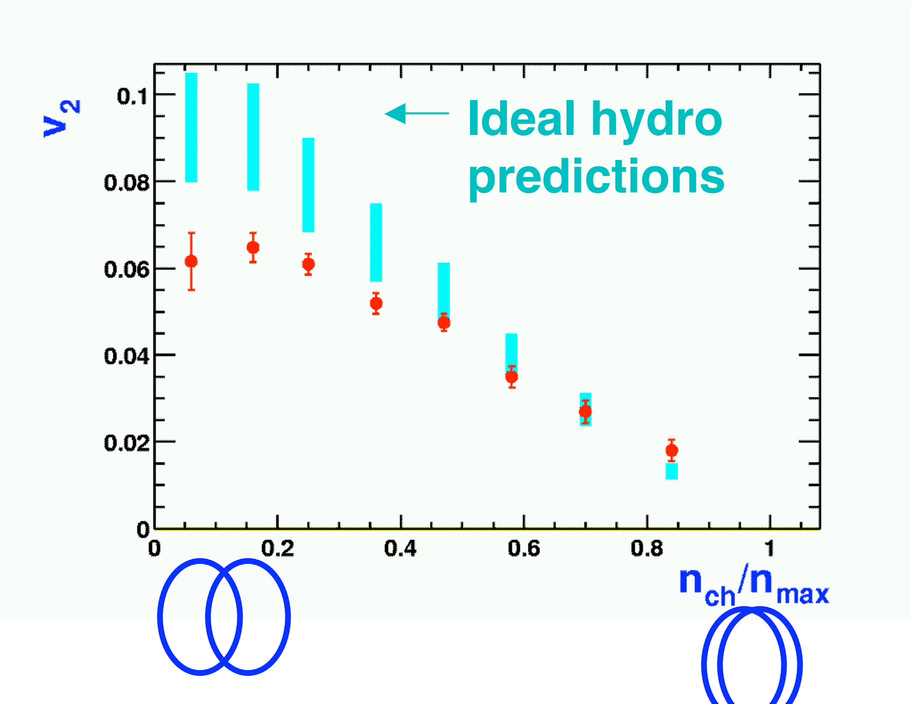
Perfect liquid conjecture



**Measuring transport properties: diffusion, sound, viscosity ….
are new to particle physics!**

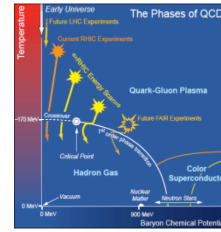


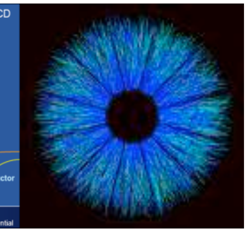
First STAR paper:
K. H. Ackermann et. al. PRL86 (2001)



Data approaches ideal HYDRO calculations for central collisions

Ideal hydrodynamics simulations describe the measured anisotropies in the low transverse momentum region, $p_T \simeq 1 GeV/c$

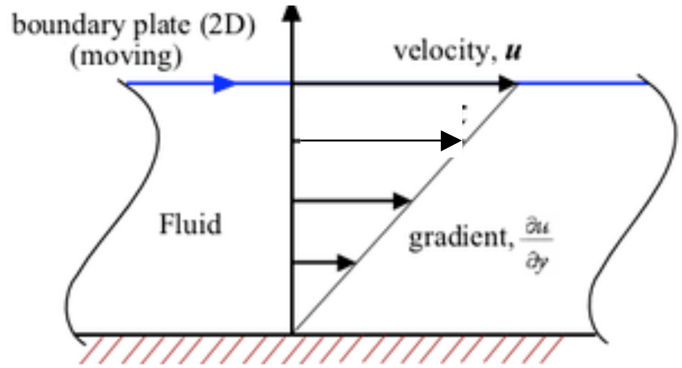




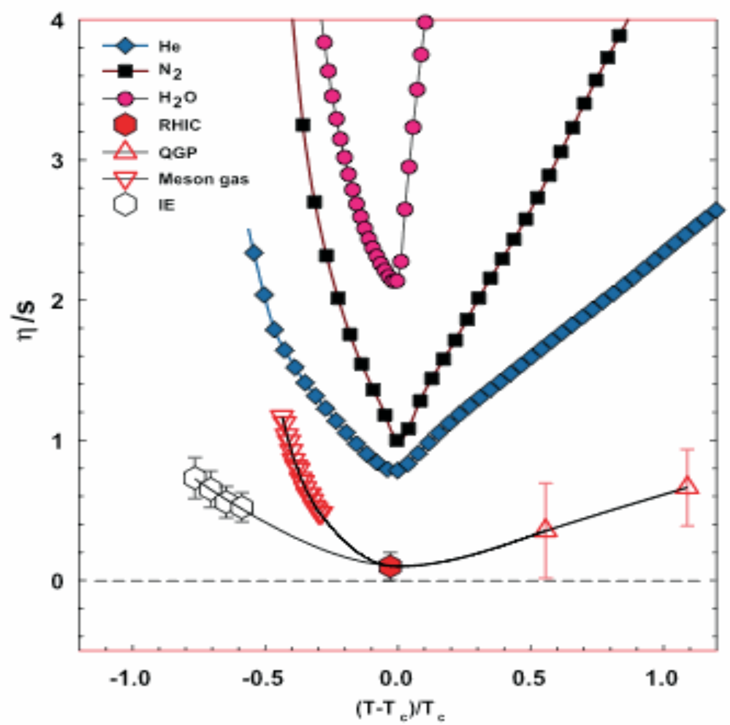
Viscosity

Measure of resistance of a fluid which is deformed by shear stress

$$T_{yx} = -\eta \frac{dv_x}{dy}$$



Perfect Fluids …..



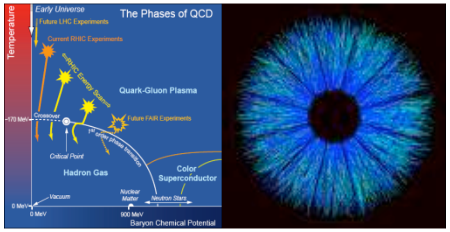
Measure of fluidity is provided by η / s

> **Fascinating observation!**
> - **Quark Gluon Plasma**
>   **T ~ 200 MeV ~ 10^{12}K**
> - **High temperature superliquid!**

Shear viscosity relative to entropy density of a system indicates:

- **how strongly a system is coupled?**
- **how perfect the liquid is?**

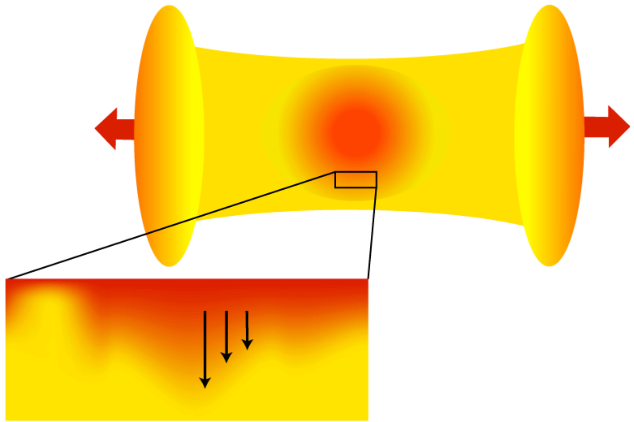
Measurement of viscosity based on p_T correlations



Gavin and Aziz, Phys. Rev. Lett. 97 (2006) 162302

- Viscous friction arises as fluid elements flow past each other, thereby reducing the relative velocity: damping of radial flow.
- T_{zr} changes the radial momentum current of the fluid, $T_{zr} = -\eta\, \partial v_r / \partial z$
- Diffusion equation for the momentum current

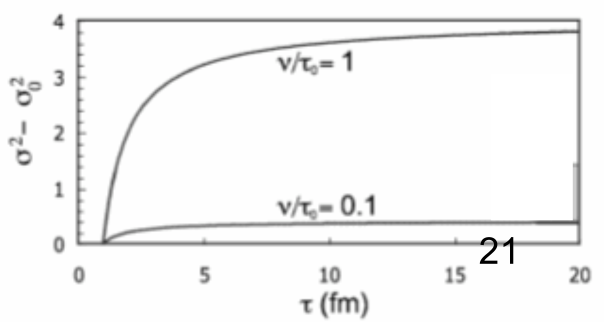
$$\left(\frac{\partial}{\partial t} - \nu \nabla^2 \right) g_t = 0$$



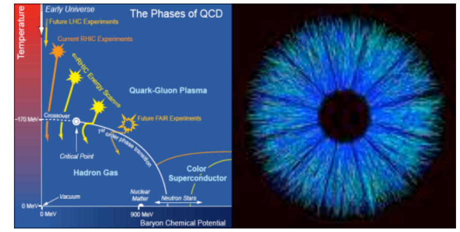
- Viscosity reduces fluctuations, distributes excess momentum density over the collision volume: broadens the rapidity profile of fluctuations.
- Width of the correlation grows with diffusion time (system lifetime) relative to its original/initial width

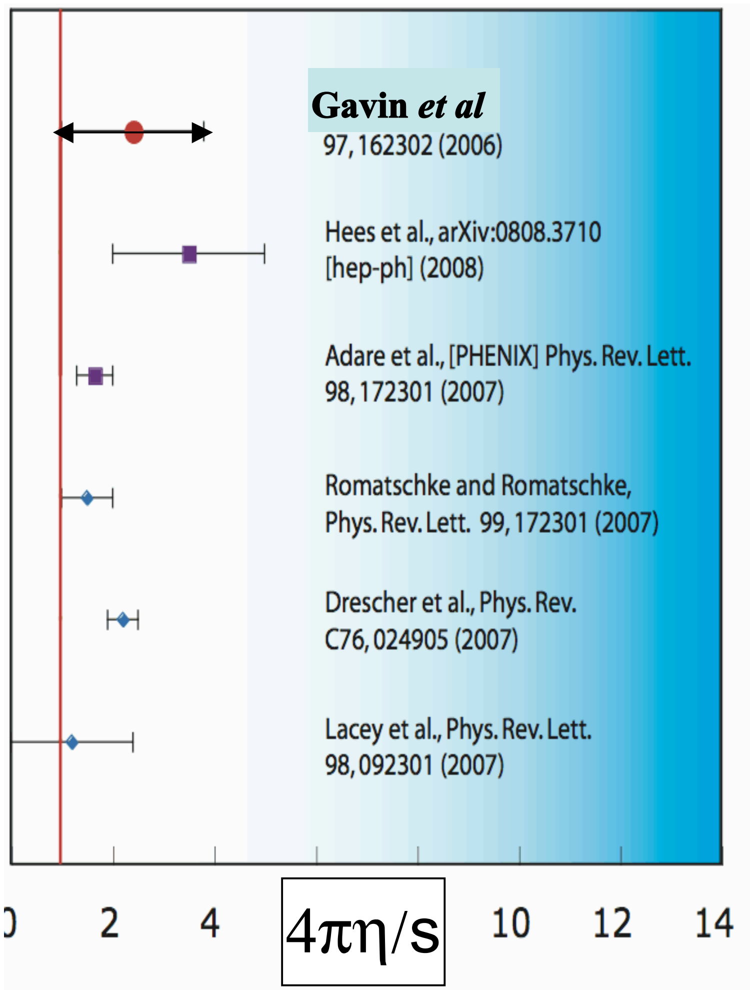
$$\sigma^2 = \sigma_0^2 + 2\Delta V(\tau_f)$$

$$\Delta V(\tau) = \frac{2\nu}{\tau_0}\left(1 - \frac{\tau_0}{\tau}\right)$$



Estimate from two particle correlations





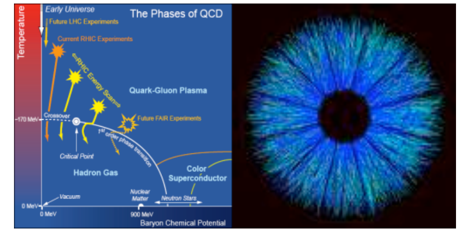
$$0.08 < \eta / s < 0.3$$

Based on:

p_T correlations, $\eta / s \approx 0.08$
STAR, J. Phys. G32. L37, 2006 (AuAu 200 GeV)

Number density correlations, $\eta / s \approx 0.3$
STAR, PRC 73, 064907, 2006 (AuAu 130 GeV)

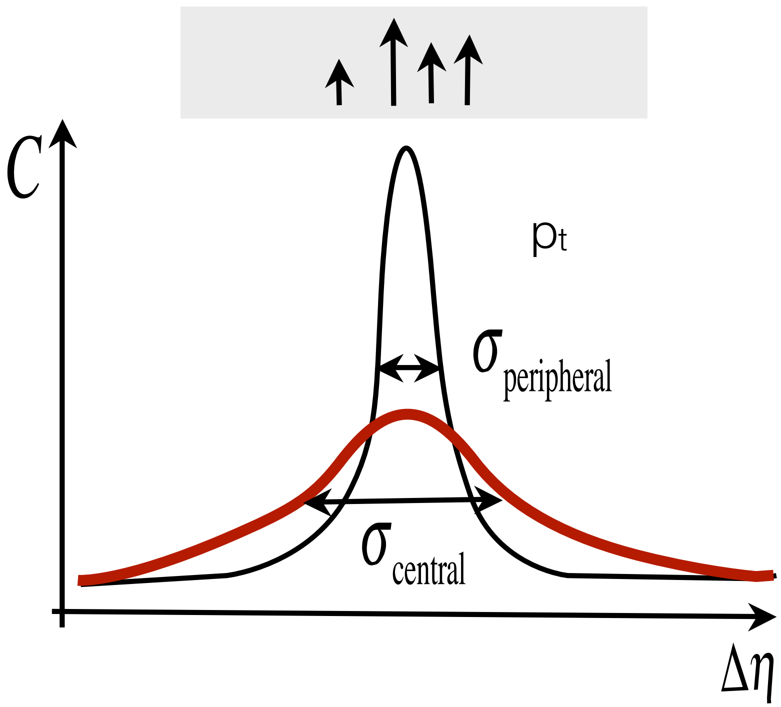
But, ……
Proper estimation of viscosity to entropy density ratio requires a study of transverse momentum flow which includes both…..



Rheometry of QGP….

- ***Integral*** **correlation function (Gavin & Aziz, Phys. Rev. Lett. 97 (2006) 162302).**

$$C(\Delta\eta) = \langle p_{\perp,1} p_{\perp,2} \rangle - \langle p_\perp \rangle^2 \qquad \langle p_{t1} p_{t2} \rangle \equiv \frac{1}{\langle N \rangle^2} \left\langle \sum_{\text{pairs } i \neq j} p_{ti} p_{tj} \right\rangle \qquad \langle p_t \rangle \equiv \frac{1}{\langle N \rangle} \left\langle \sum p_{ti} \right\rangle$$



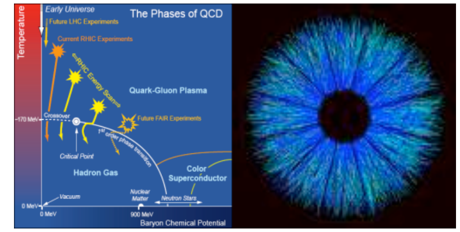
$$\sigma_c^2 - \sigma_0^2 = 4\upsilon\left(\tau_0^{-1} - \tau_f^{-1}\right)$$

$$\upsilon = \frac{\eta}{T_c s}$$

η = shear viscosity
T_c = critical temperature
S = entropy density

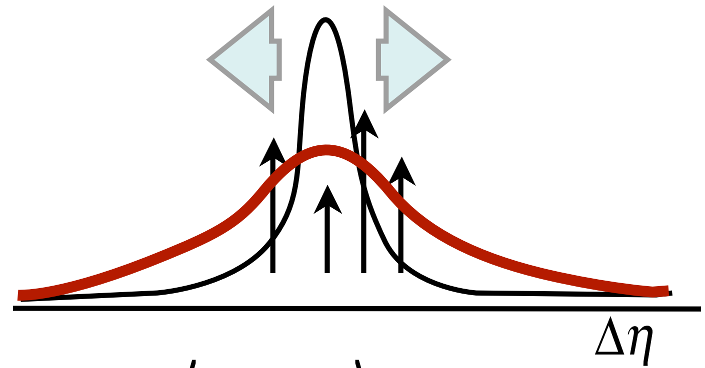
τ_0 = formation time
τ_f = freeze-out time

This work: differential $p_T p_T$ correlations..



$$C(\Delta\eta,\Delta\varphi)=\frac{\left\langle \sum_{i=1}^{n_1}\sum_{j\neq i=1}^{n_2} p_i p_j \right\rangle}{\langle n_1\rangle\langle n_2\rangle}-\langle p_{t,1}\rangle\langle p_{t,2}\rangle$$

$$\Delta\eta=\eta_1-\eta_2 \qquad \Delta\varphi=\varphi_1-\varphi_2$$



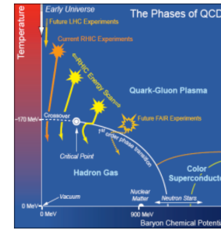
Inclusive average p_T: $$\langle p_{t,i}\rangle(\eta_i,\varphi_i)=\frac{\left\langle \sum_{k=1}^{n_1} p_{t,k}\right\rangle}{\langle n_i\rangle}$$

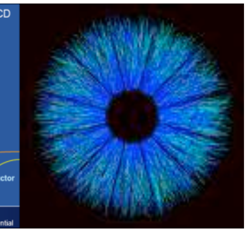
Transverse momentum of particles in bin *i*: $p_{t,i}$

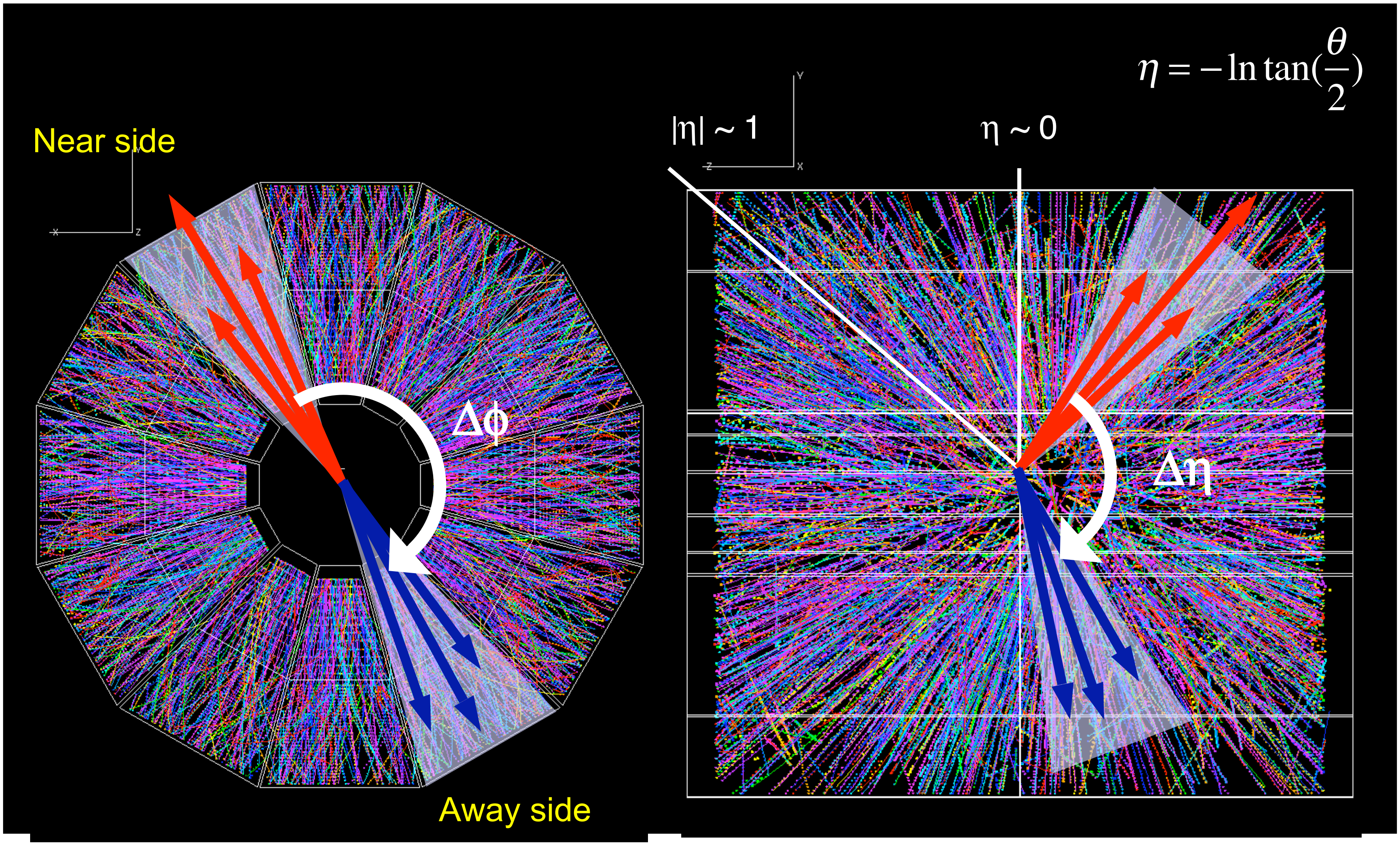
Number of particles in bin *i* $\quad n_i\equiv n_i(\eta_i,\varphi_i),\quad i=1,2$

Broadening $$\sigma_c^2\approx\sigma_{Diffusion}^2+\sigma_0^2$$

2-D ($\Delta\eta$-$\Delta\phi$) correlations

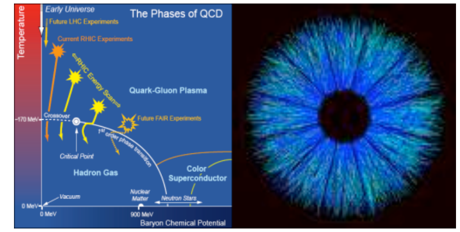


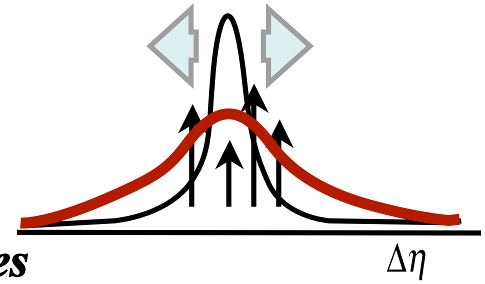




Monika Sharma
Brookhaven National Lab, Mar 30, 2010

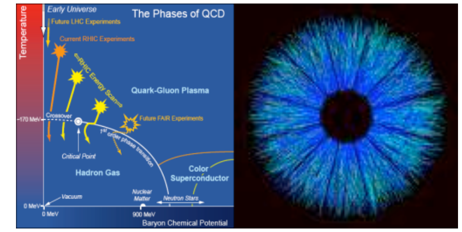
Theoretical/Physics Caveats



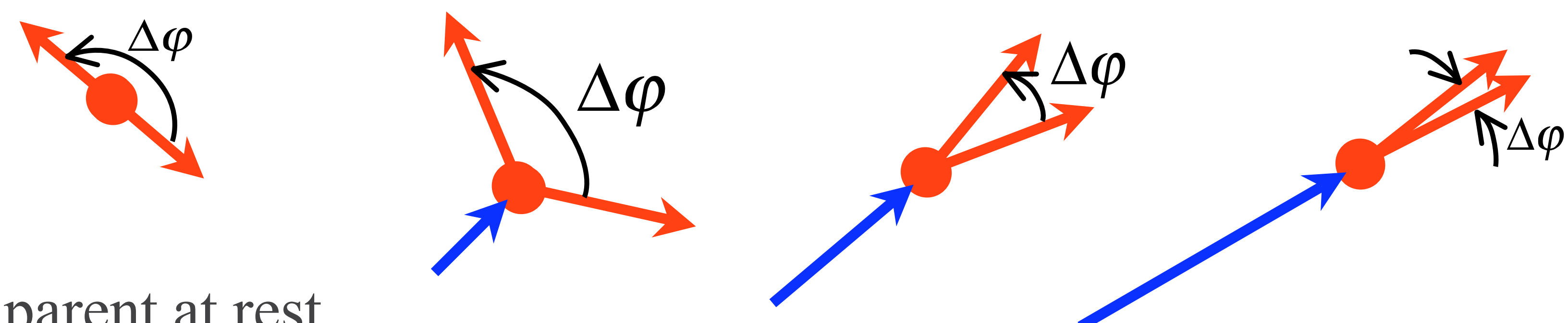


- The system temperature and viscosity vary through the lifetime of the collision system.
  - Our measurement will yield ***time averaged quantities***
- Freeze out times must be inferred from other data + model
- Other effects may contribute to the longitudinal shape of the correlation function
  - Decays, jets, radial flow, CGC, etc
  - Jet expected to have minor impact in the momentum range considered in this analysis.
  - Diffusion expected to dominate the broadening
- A detailed interpretation of the measurements requires collision models that provide comprehensive understanding of HI data.

Dynamical Effects (1): Resonance Decays



- **An increase in system temperature and/or radial flow implies kinematical focusing of the decay products: *narrowing of the correlation function*.**



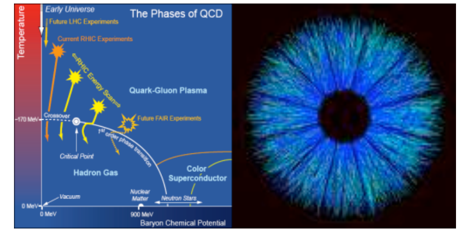
parent at rest

low temperature
or radial velocity

medium temperature
or radial velocity

high temperature
or radial velocity

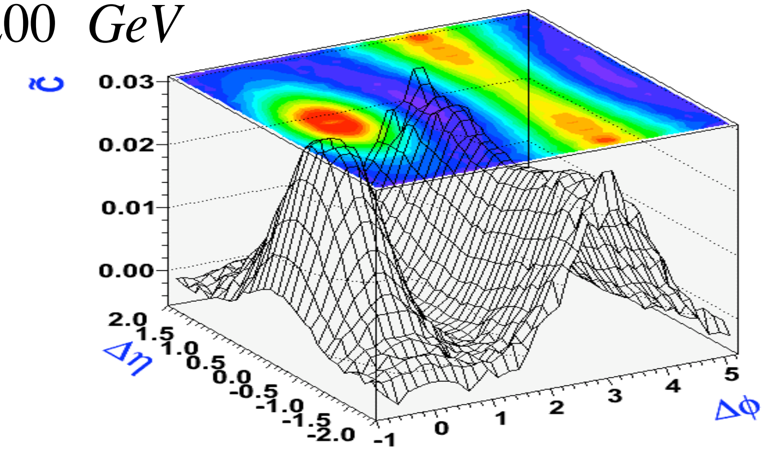
Dynamical Effects (2): Radial Flow



- Based on PYTHIA p+p collisions at $\sqrt{s} = 200 \;\; GeV$

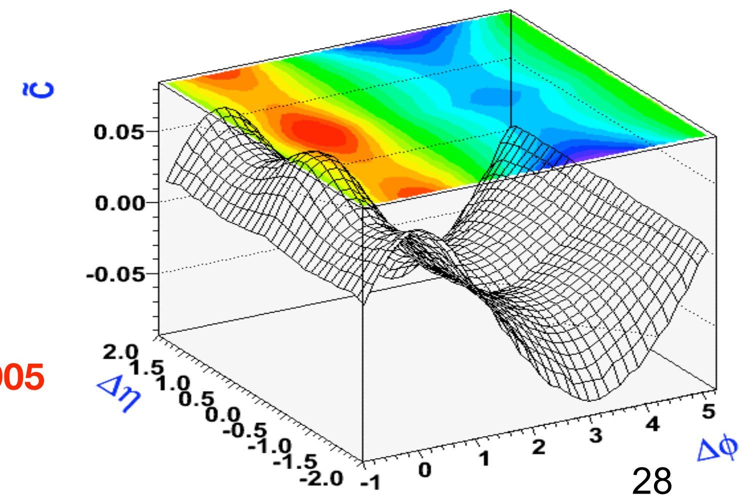
Particle Selection: $0.2 < p_T < 2.0$ GeV/c
$|\eta| < 1$

- PYTHIA Simulation including radial flow (transverse boost) with v/c = 0.3



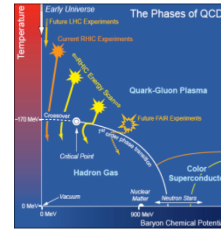
- Near-side kinematic focusing, formation of ridge-like structure,
- Different shapes
- Narrowing of near side

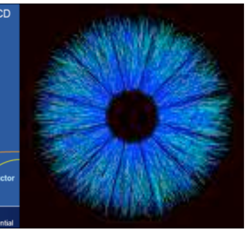
S. A. Voloshin, arXiv:nucl-th/0312065
C. Pruneau, et al., Nuclear. Phys. A802, 107 (2008)

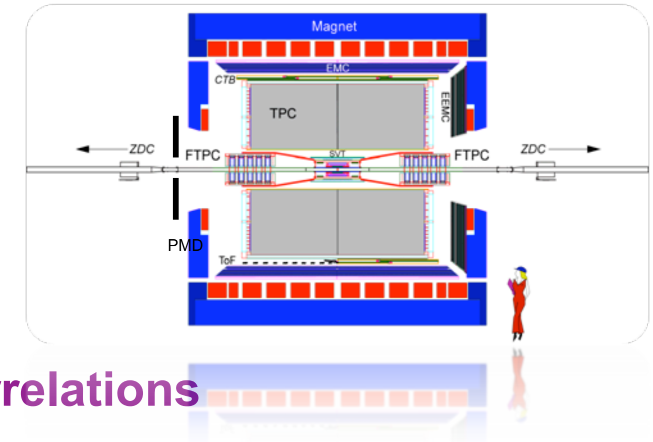


M. Sharma & C. A. Pruneau, Phys. Rev. C 79 (2009) 024905

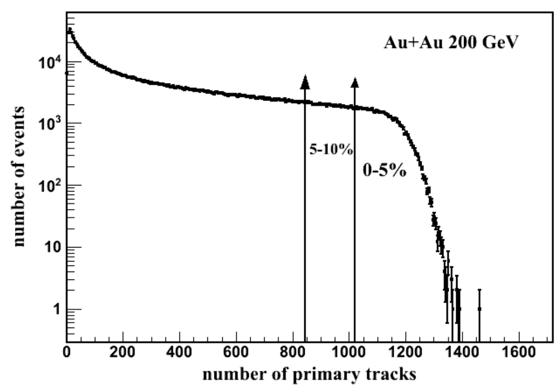
STAR Analysis



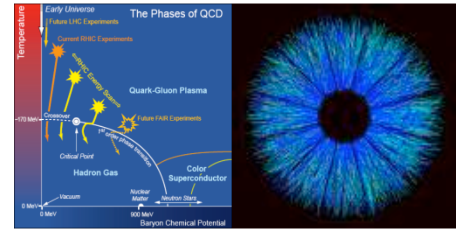




- Data from STAR TPC, 2π coverage
- Dataset: RHIC run IV: AuAu 200 GeV
- Events analyzed: 10 Million
- Minimum bias trigger
- Track kinematic cuts
    - o Goal: measure medium properties i.e., **Bulk Correlations**
    - o $|\eta|<1.0$
    - o $0.2< p_T < 2.0$ GeV/c, **No trigger and associated particle**
- Analysis done vs. collision centrality measured based on multiplicity in $|\eta|<1.0$

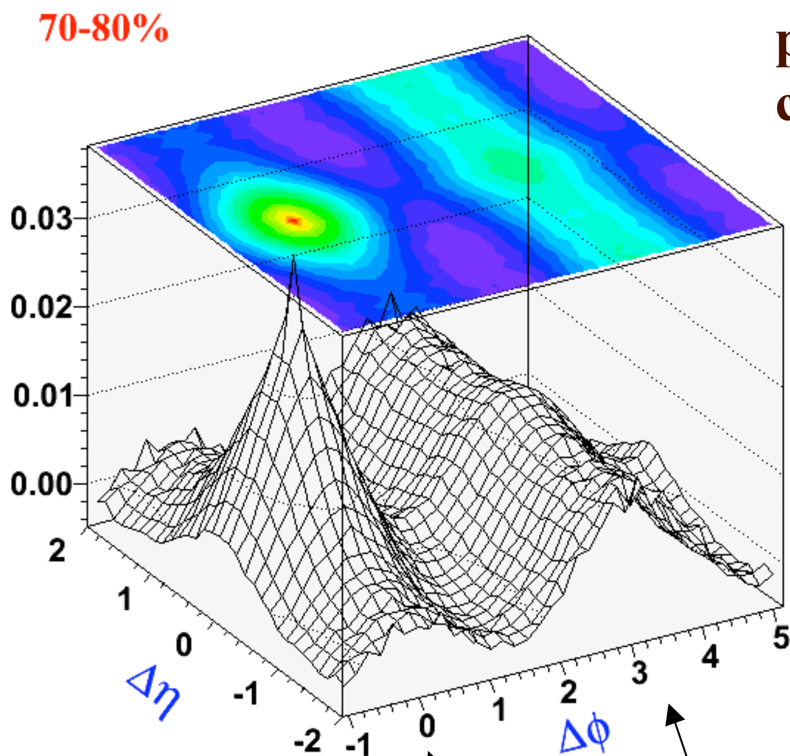


Slices: 0-5%, 5-10%……. 70-80%



Results….

> **Shape of the correlation function partly determined by momentum conservation effects…..**
>
> **N. Borghini arXiv:0707.0436**

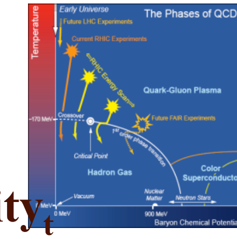


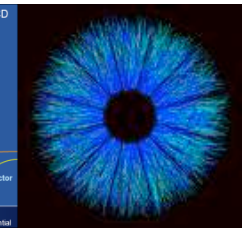
STAR Analysis PRELIMINARY

Near side

Away side

- ✓ Sharp peak observed at $\Delta\phi \sim 0$ and an away-side ridge at $\Delta\phi \sim \pi$

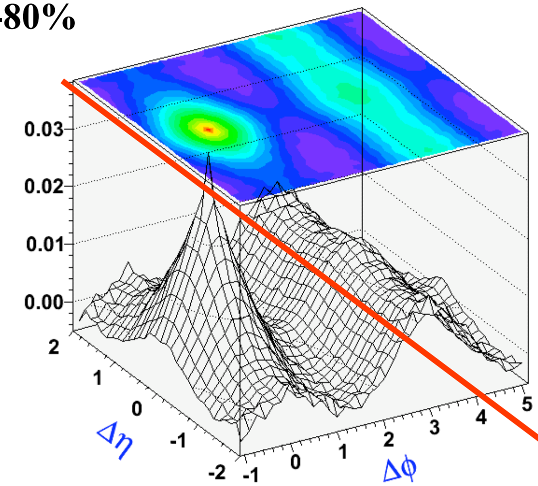




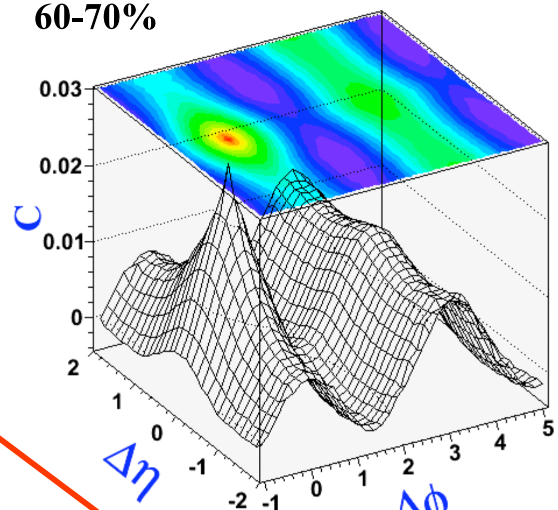
Results….

Increasing centrality

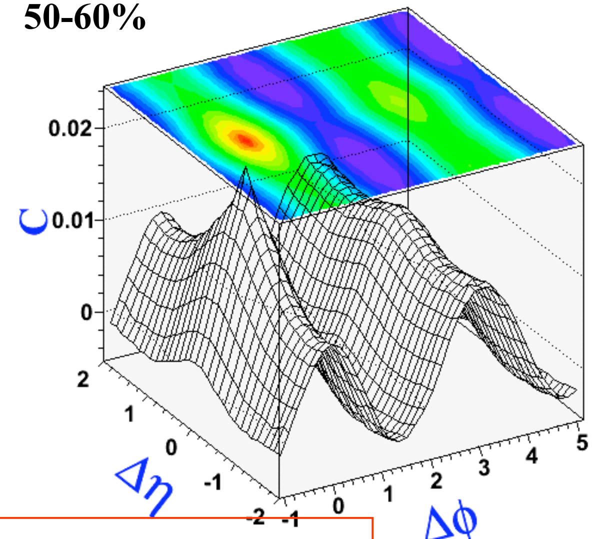
70-80%



60-70%

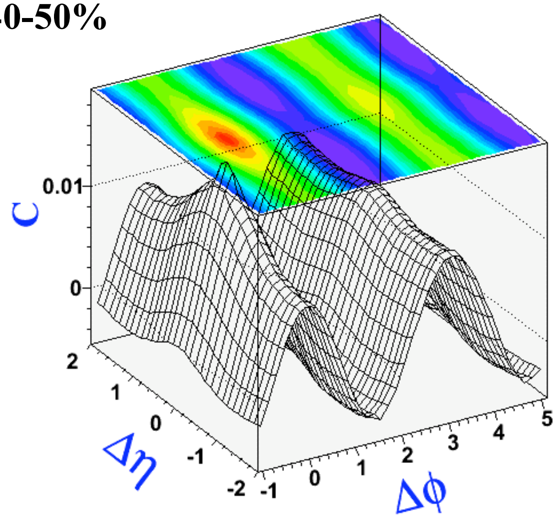


50-60%

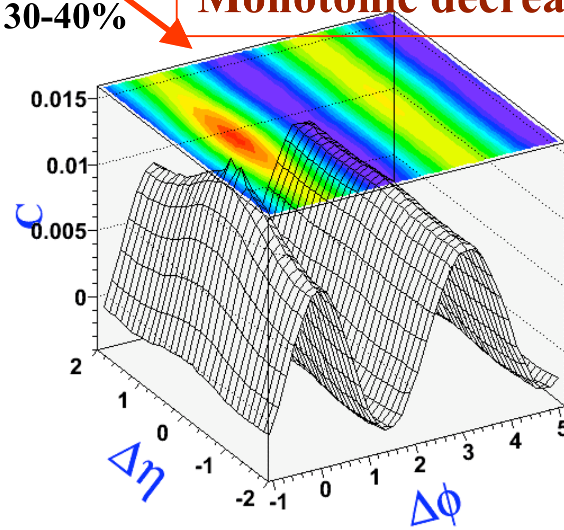


Monotonic decrease in magnitude

40-50%

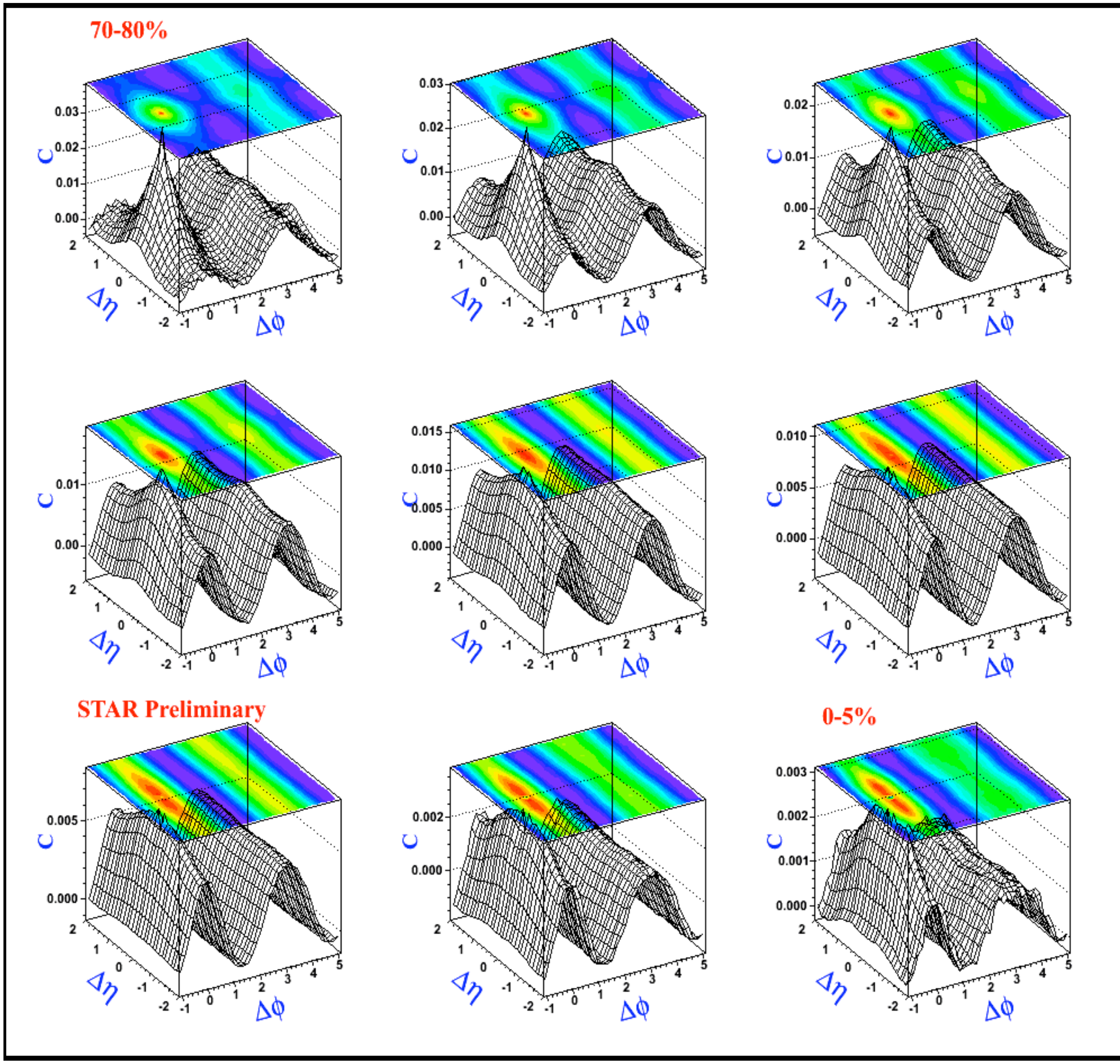


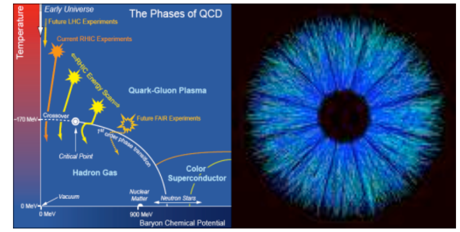
30-40%



- ✓ **Formation of ridge-like structure on near-side**
- ✓ **cos(2Δϕ) modulation (elliptic flow)**

Results.....



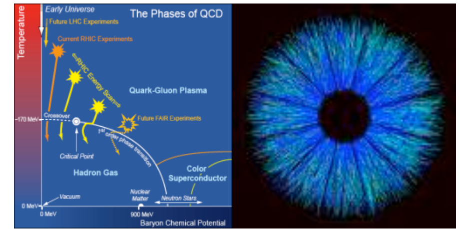


- Prominent near side peak in peripheral collisions
- Ridge-like structure on the away-side (momentum conservation) in peripheral collisions.

- Monotonic reduction of the correlation amplitude with increasing N_{part}.
- Evidence of elliptic flow component in mid-central central collisions.

- Emergence of a near-side ridge with increasing N_{part}.

Technical issues....



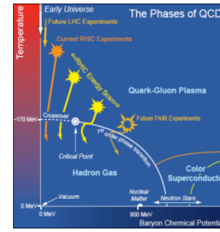
- ✓ Centrality selection technique
- ✓ Dependence of the correlation function on Z-vertex
- ✓ Dependence of the correlation function on magnetic field direction
- ✓ Track merging effects

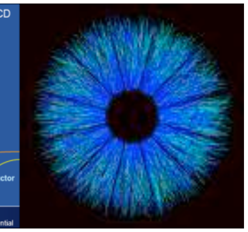
Track merging effect

$\vec{B} \otimes$

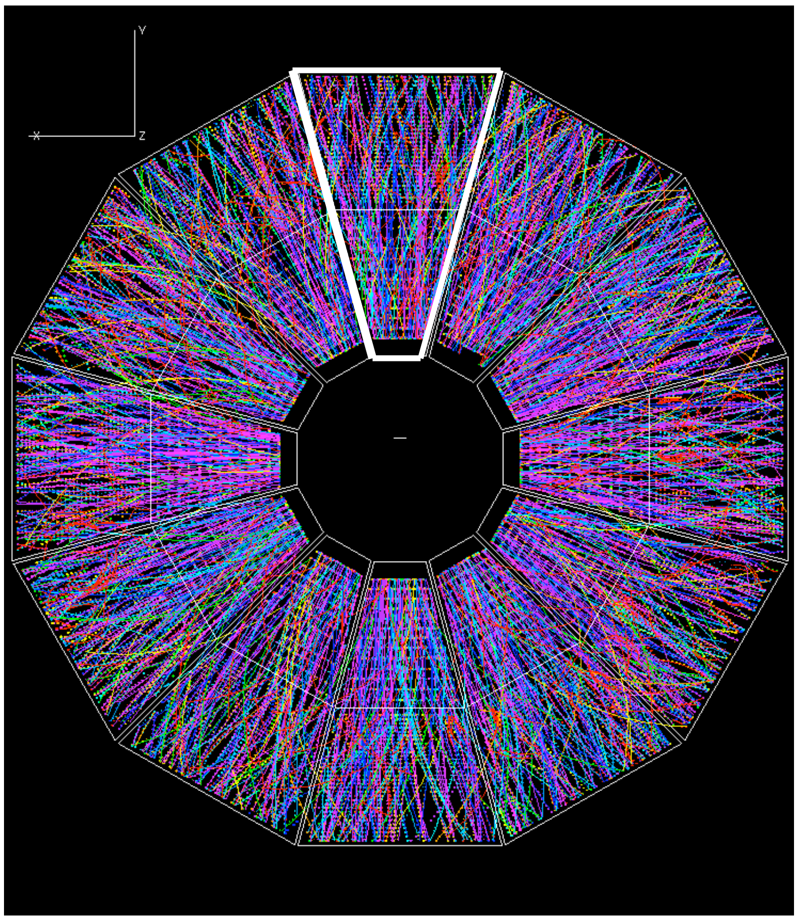
$p_{T1} = 1.0 GeV / c$

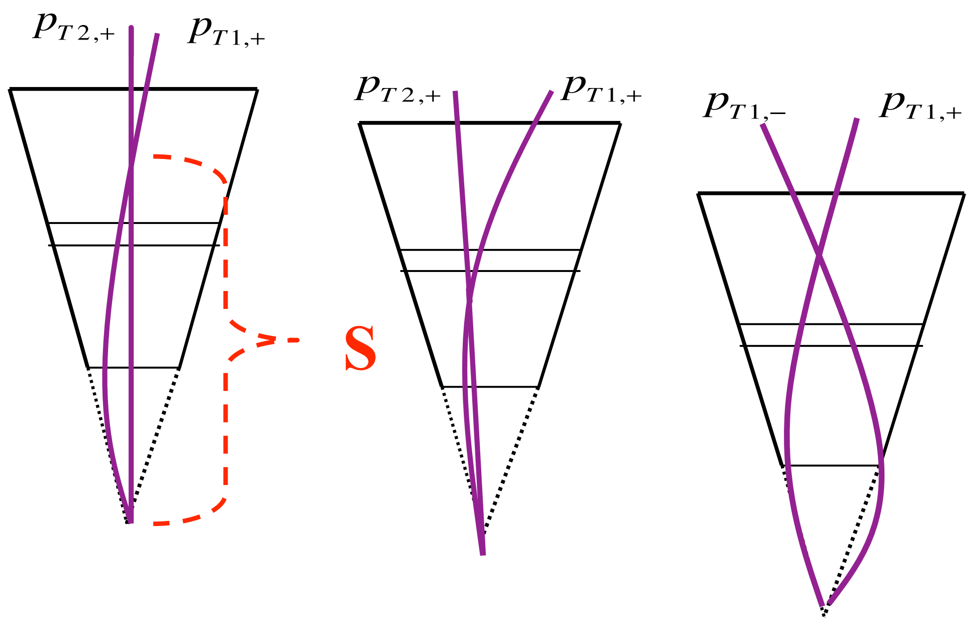
$p_{T2} = 2.0 GeV / c$



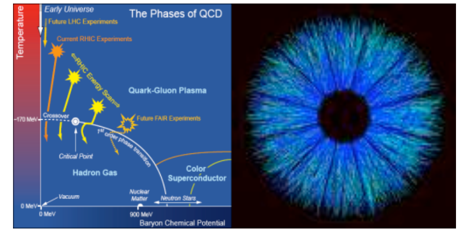


Graphical visualization of crossing point position in the xy plane

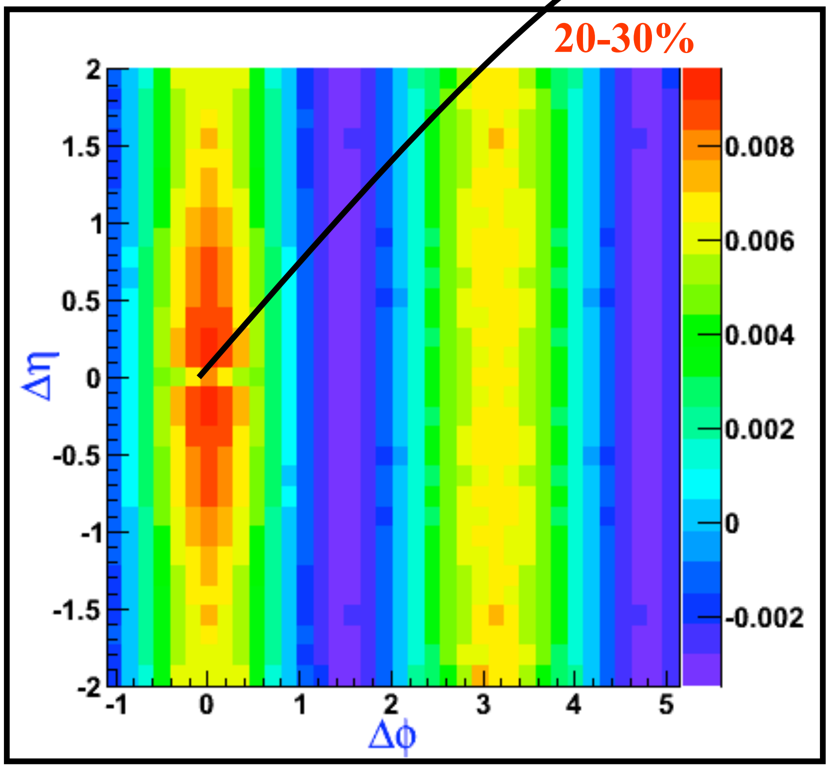




"S", shows up in azimuth as a point where tracks have merged.



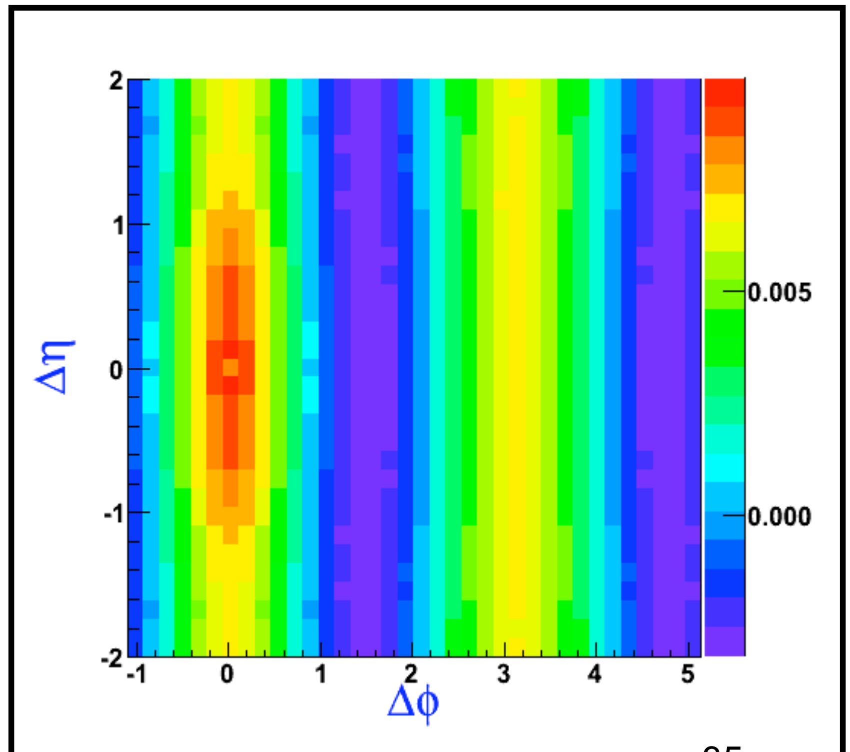
Results…



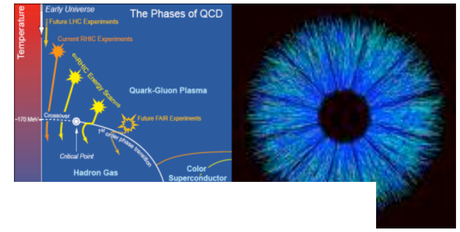
Reduced pair yield observed at $\Delta\eta \sim \Delta\phi \sim 0$

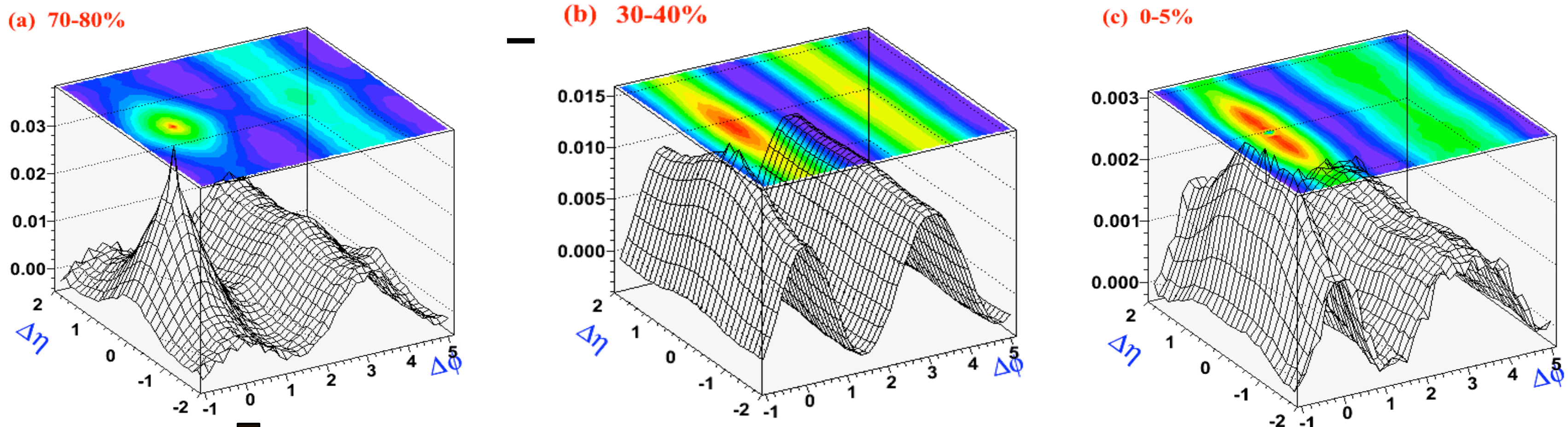
Shown for one Z-bin only 0<Z<2.5cm

Correlation function corrected for track merging effects.
Shown for full statistics

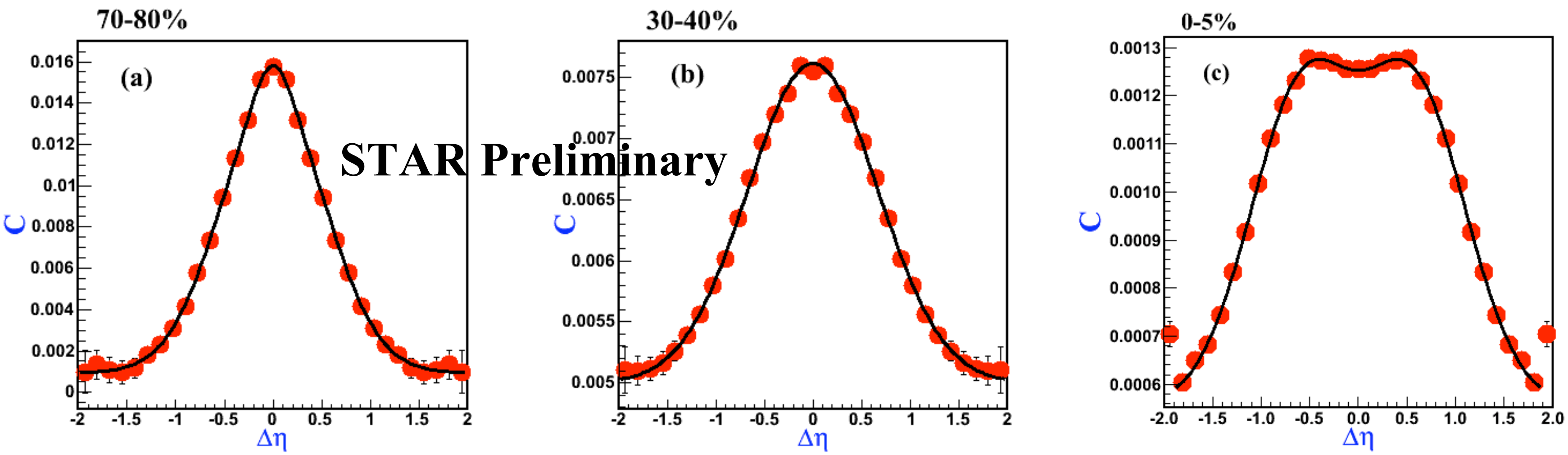


Results…



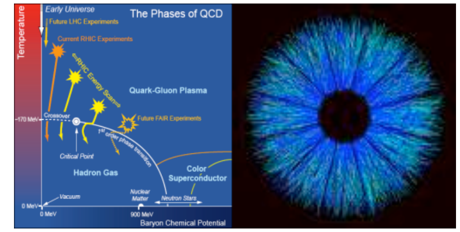


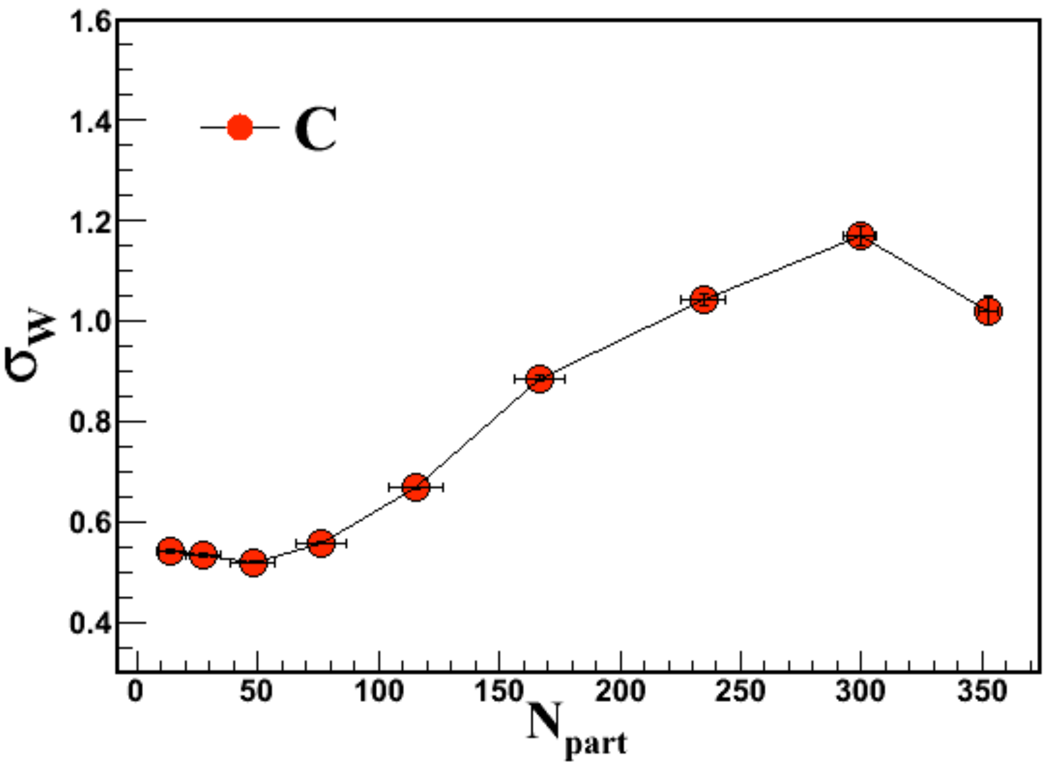
Near-side projection



Fit function $C(b,a_w,\sigma_w,a_n,\sigma_n) = b + a_w \exp(-\Delta\eta^2 / 2\sigma_w{}^2) + a_n \exp(-\Delta\eta^2 / 2\sigma_n{}^2)$

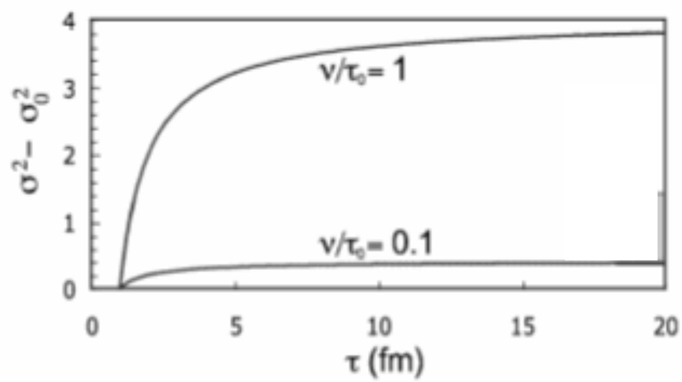
Correlation width vs. collision centrality





- Width approximately constant in most peripheral bins.
  - Incomplete thermalization?
  - Radial flow effects?
  - Event centrality selection technique?
- Linear increase for N_{part} > ~100
- Decrease in most central collisions

Working on finalizing the systematic errors



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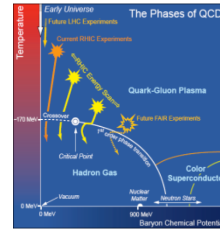
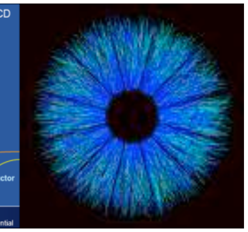
Brookhaven National Lab, Mar 30, 2010

Estimation of shear viscosity





$$\sigma_c^2 - \sigma_0^2 = 4\upsilon\left(\tau_0^{-1} - \tau_f^{-1}\right)$$

$\sigma_0 = 0.542 \pm 0.003$ $\tau_0 = 1$ **fm/c**

$\sigma_c = 1.021 \pm 0.029$ $\tau_f = 20$ **fm/c**

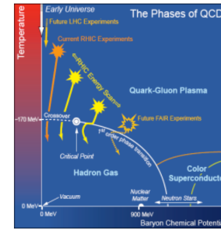
- ✓ **References for freeze out time estimates in peripheral collisions**
  - **Bjorken PRD 27 (1983)**
  - **Teaney, Nucl. Phys. 62 (2009)**
  - **Dusling et al. arXiv:0911.2720**
  - **M. Luzum & P. Romatschke arXiv:0901.4588**

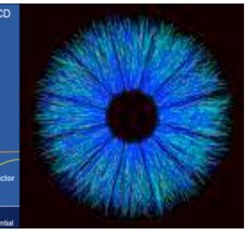
$$\frac{\eta}{s} = 0.17 \pm 0.02(stats.)$$ **STAR Preliminary**

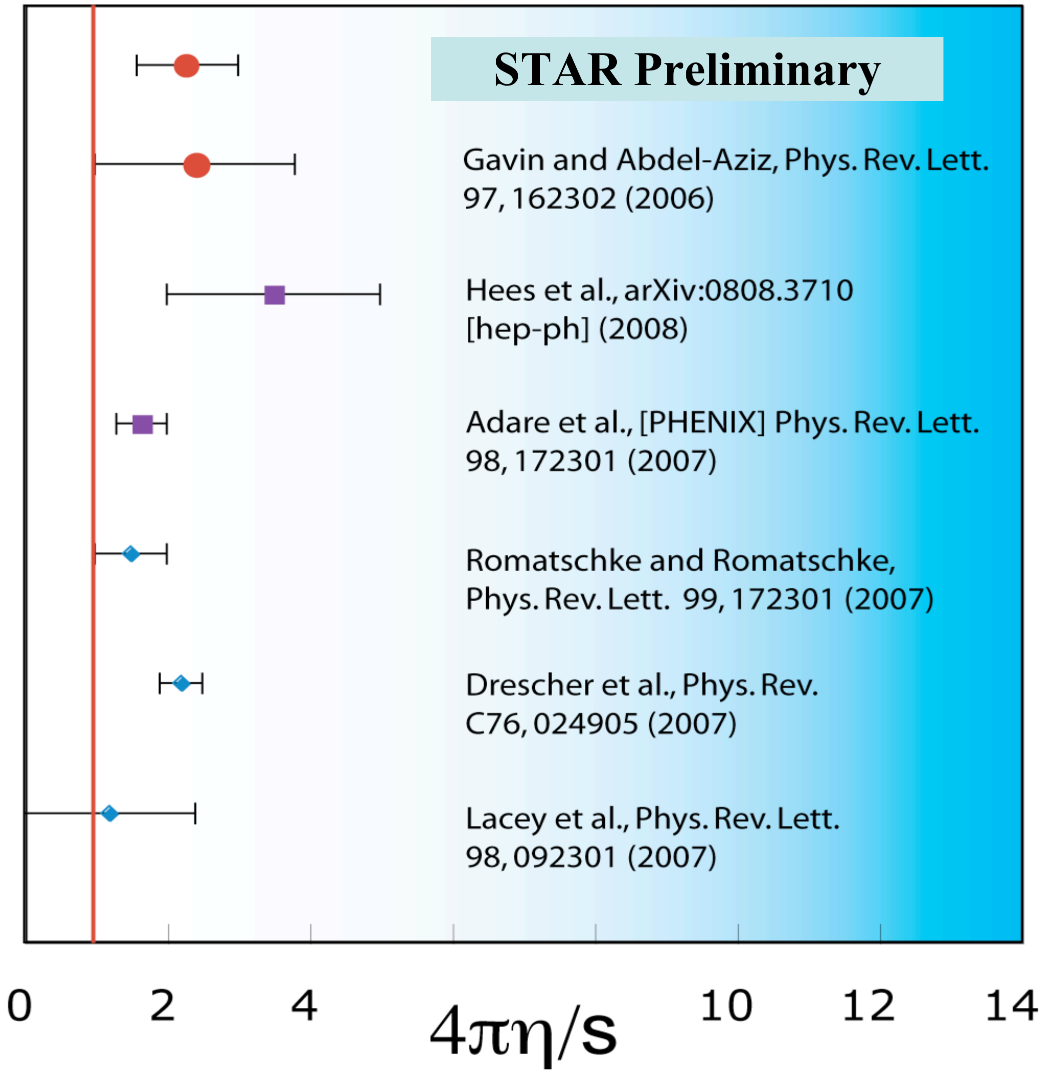
Non Gaussian shape observed in central collisions suggests broadening could have contributions from other phenomena as well.

The above value is thus an upper limit of the time averaged viscosity if $\tau_0 = 1\,fm/c$

η/s estimates.....







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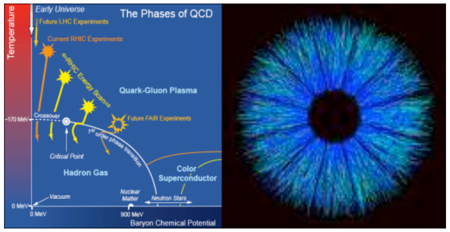
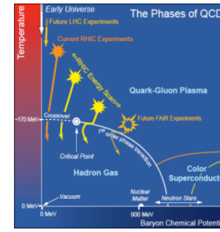
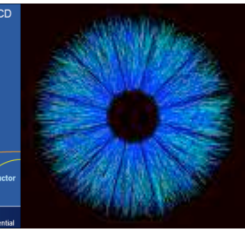


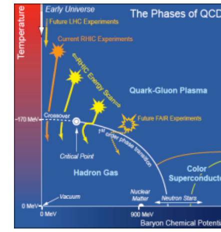
Summary - III

- **Presented first measurements of viscosity based on transverse momentum correlations using C at RHIC.**
- **C exhibits near-side ridge-like structure in momentum space for the most central collisions.**
- **The over-all shape of the correlation function evolves significantly from peripheral to the most-central collisions.**
- **We use a near-side projection (i.e., $|\Delta\phi| < 1.0$) of C to determine the evolution of momentum correlations with centrality.**
- **Based on the formula given by Gavin *et al* and common estimates of freeze-out times, we estimate an upper bound on the viscosity of the matter produced in Au+Au collisions.**

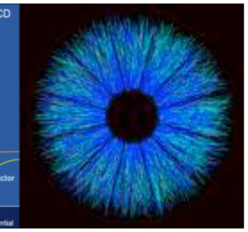
Back-up

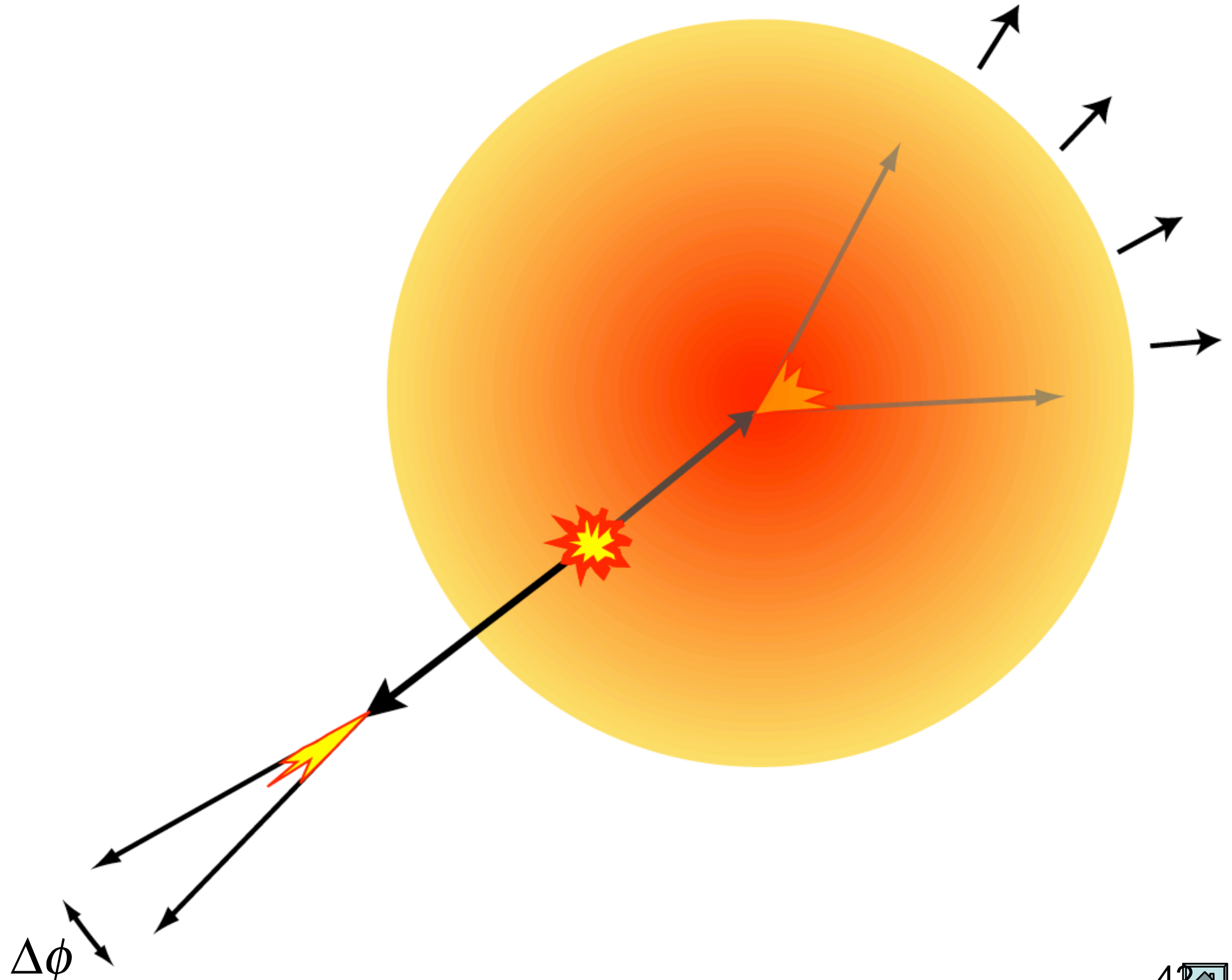

The Phases of QCD
Temperature
Early Universe
Future LHC Experiments
Current RHIC Experiments
RHIC Energy Scan
Quark-Gluon Plasma
~170 MeV
Crossover
Future FAIR Experiments
1st order phase transition
Critical Point
Hadron Gas
Color
Superconductor
Vacuum
Nuclear
Matter
Neutron Stars
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential



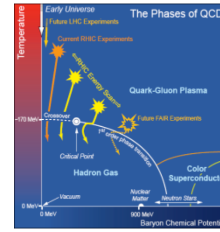


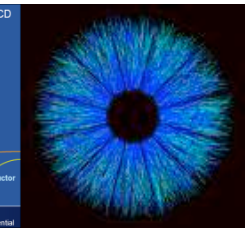
The Phases of QCD
Early Universe
Temperature
Quark-Gluon Plasma
Critical Point
Hadron Gas
Color
Superconductor
Baryon Chemical Potential

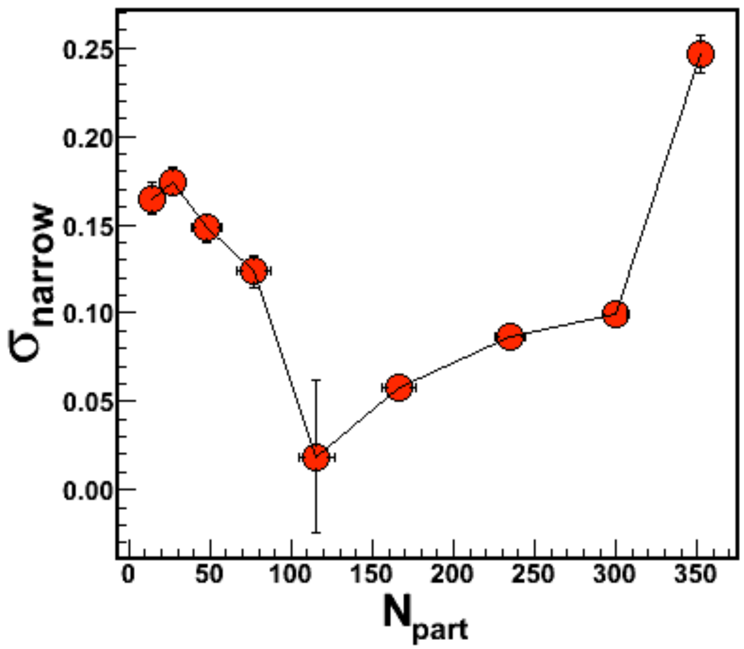


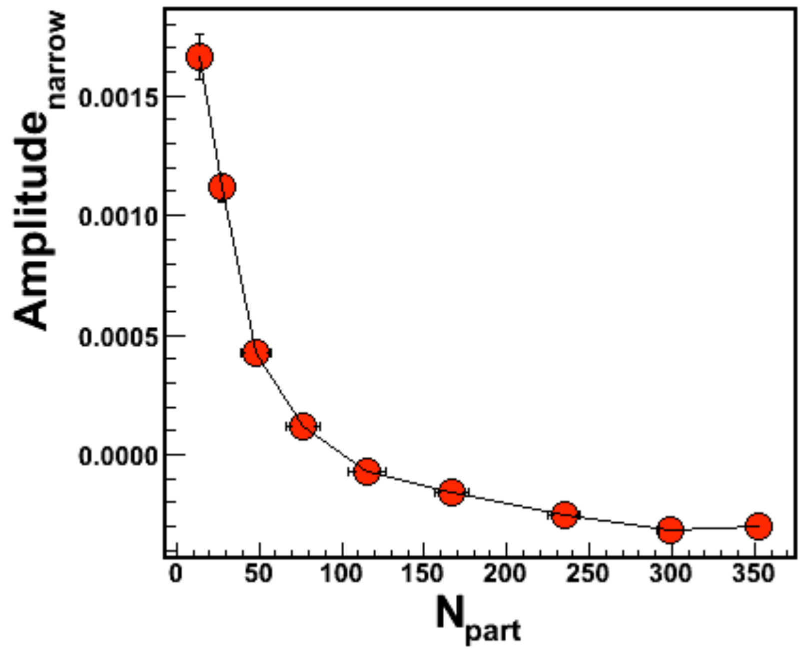


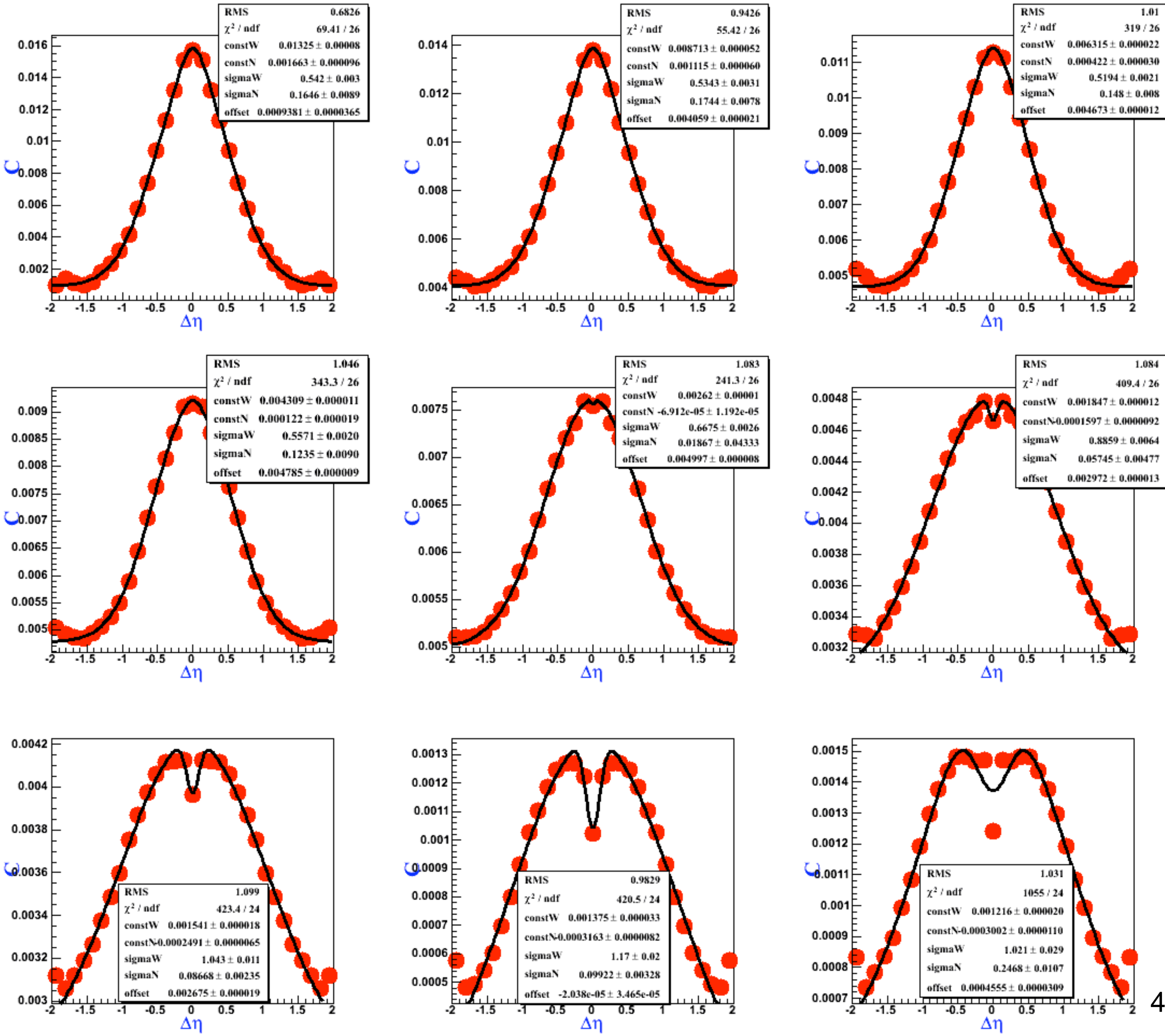
$\Delta\phi$


The Phases of QCD
Temperature
Early Universe
Quark-Gluon Plasma
Hadron Gas
Color Superconductor
Baryon Chemical Potential

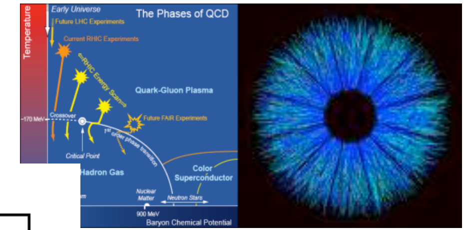


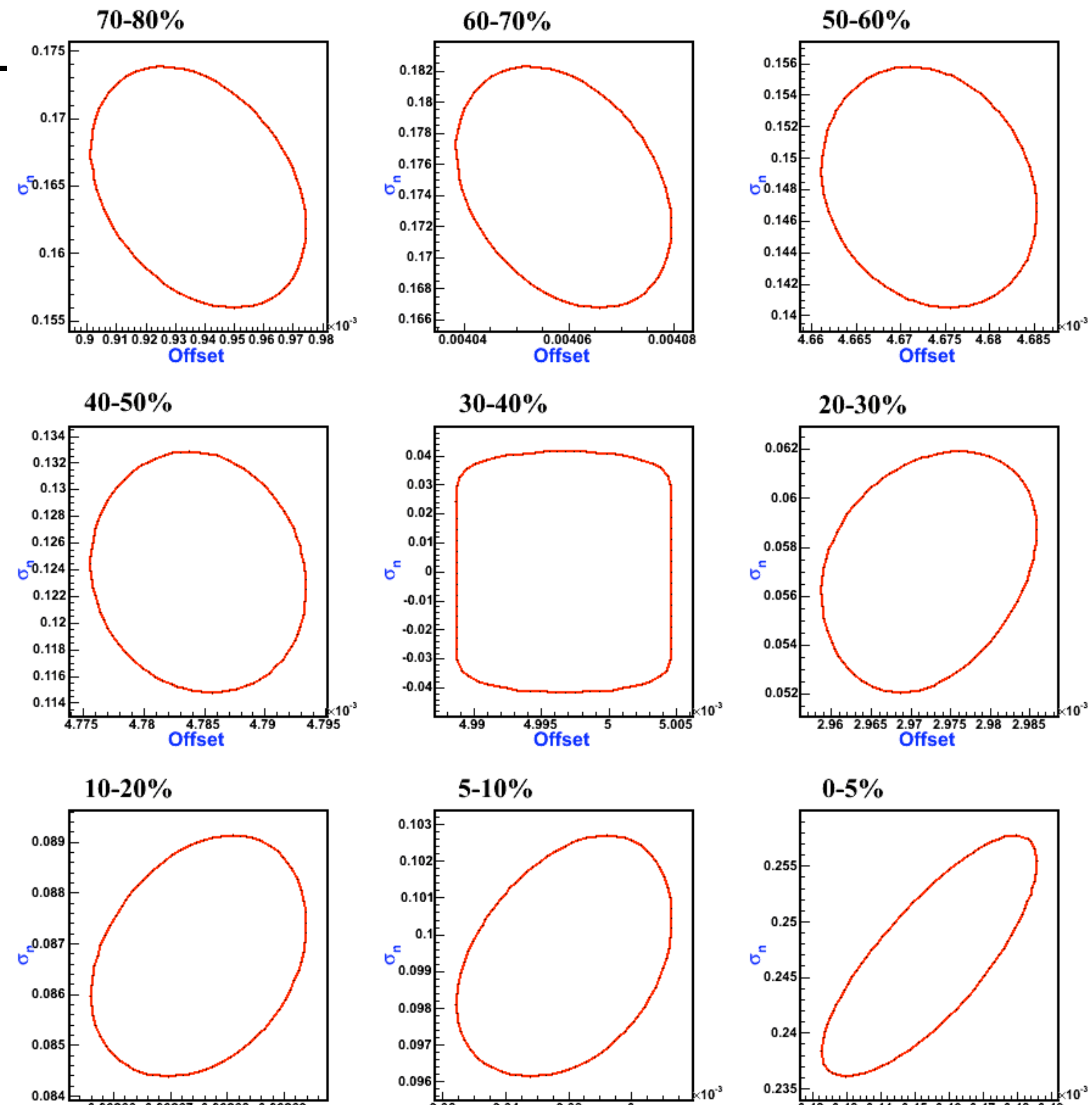

σ_{narrow}
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
N_{part}

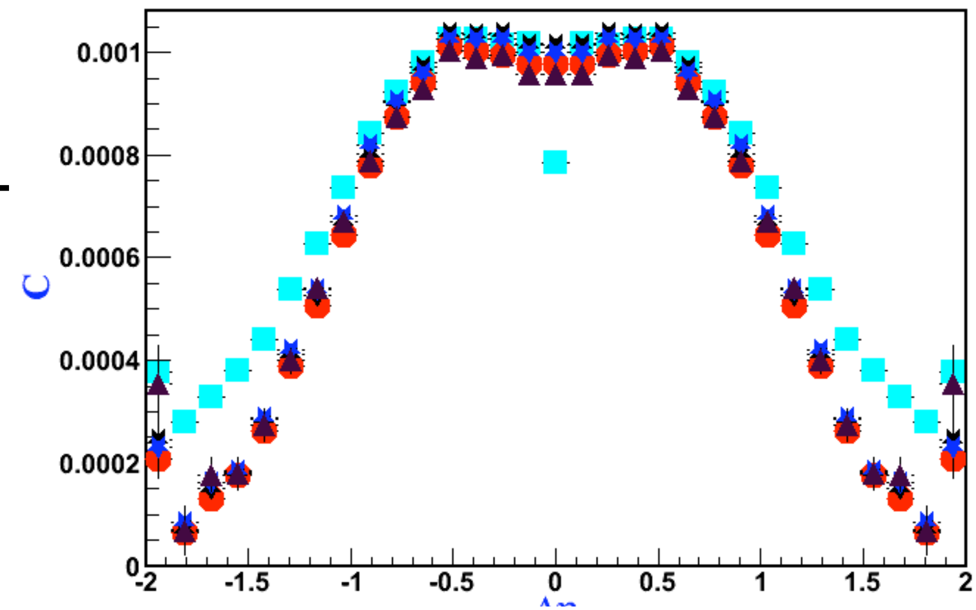

$Amplitude_{narrow}$
0.0015
0.0010
0.0005
0.0000
0
50
100
150
200
250
300
350
N_{part}



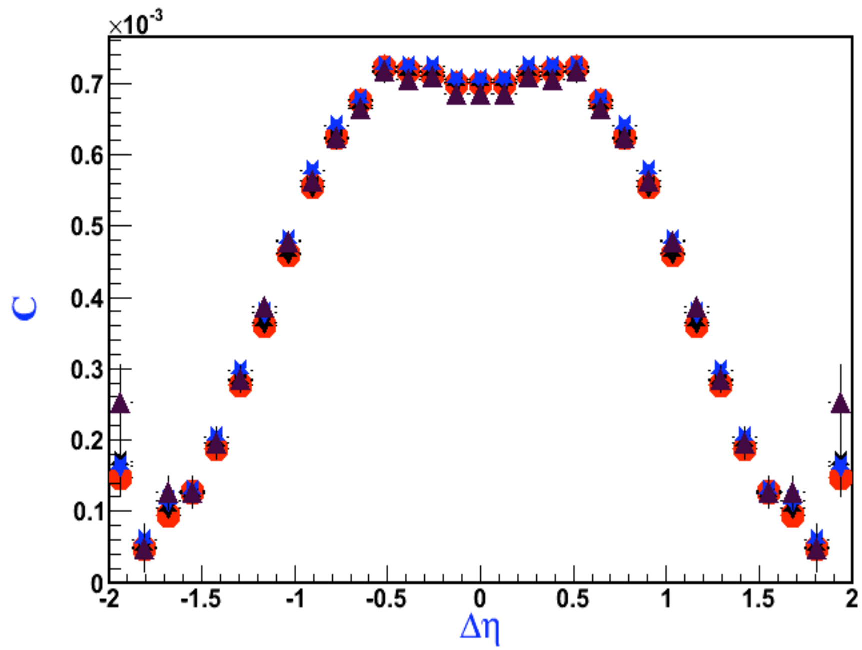
RMS 0.6826
χ² / ndf 69.41 / 26
constW 0.01325 ± 0.00008
constN 0.001663 ± 0.000096
sigmaW 0.542 ± 0.003
sigmaN 0.1646 ± 0.0089
offset 0.0009381 ± 0.0000365
RMS 0.9426
χ² / ndf 55.42 / 26
constW 0.008713 ± 0.000052
constN 0.001115 ± 0.000060
sigmaW 0.5343 ± 0.0031
sigmaN 0.1744 ± 0.0078
offset 0.004059 ± 0.000021
RMS 1.01
χ² / ndf 319 / 26
constW 0.006315 ± 0.000022
constN 0.000422 ± 0.000030
sigmaW 0.5194 ± 0.0021
sigmaN 0.148 ± 0.008
offset 0.004673 ± 0.000012
RMS 1.046
χ² / ndf 343.3 / 26
constW 0.004309 ± 0.000011
constN 0.000122 ± 0.000019
sigmaW 0.5571 ± 0.0020
sigmaN 0.1235 ± 0.0090
offset 0.004785 ± 0.000009
RMS 1.083
χ² / ndf 241.3 / 26
constW 0.00262 ± 0.00001
constN -6.912e-05 ± 1.192e-05
sigmaW 0.6675 ± 0.0026
sigmaN 0.01867 ± 0.04333
offset 0.004997 ± 0.000008
RMS 1.084
χ² / ndf 409.4 / 26
constW 0.001847 ± 0.000012
constN-0.0001597 ± 0.0000092
sigmaW 0.8859 ± 0.0064
sigmaN 0.05745 ± 0.00477
offset 0.002972 ± 0.000013
RMS 1.099
χ² / ndf 423.4 / 24
constW 0.001541 ± 0.000018
constN-0.0002491 ± 0.0000065
sigmaW 1.043 ± 0.011
sigmaN 0.08668 ± 0.00235
offset 0.002675 ± 0.000019
RMS 0.9829
χ² / ndf 420.5 / 24
constW 0.001375 ± 0.000033
constN-0.0003163 ± 0.0000082
sigmaW 1.17 ± 0.02
sigmaN 0.09922 ± 0.00328
offset -2.038e-05 ± 3.465e-05
RMS 1.031
χ² / ndf 1055 / 24
constW 0.001216 ± 0.000020
constN-0.0003002 ± 0.0000110
sigmaW 1.021 ± 0.029
sigmaN 0.2468 ± 0.0107
offset 0.0004555 ± 0.0000309
C
Δη


Temperature
Early Universe
The Phases of QCD
Future LHC Experiments
Current RHIC Experiments
Quark-Gluon Plasma
Future FAIR Experiments
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Baryon Chemical Potential

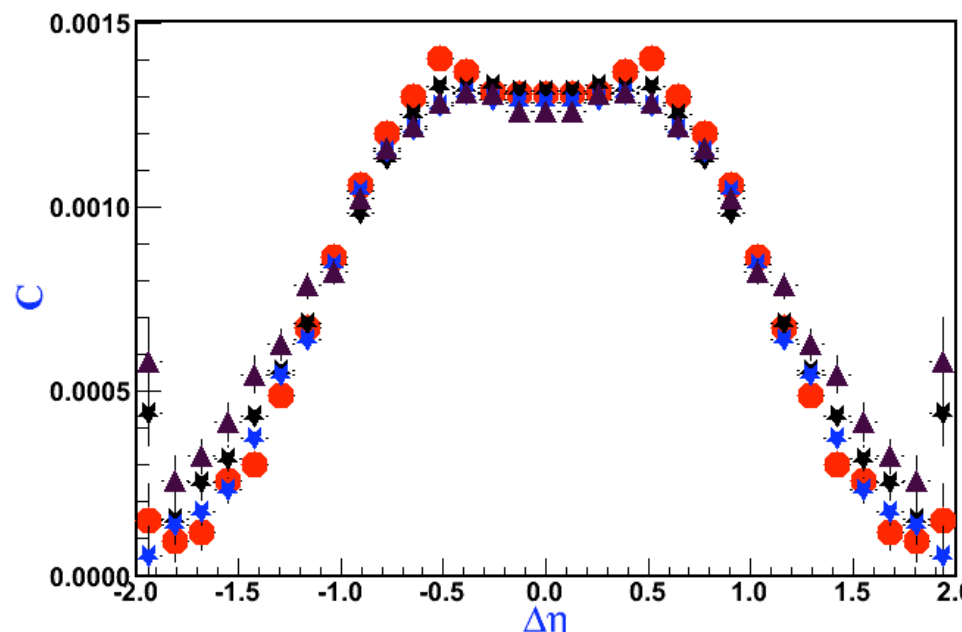

70-80%
60-70%
50-60%
40-50%
30-40%
20-30%
10-20%
5-10%
0-5%
σ_n
Offset
$\times10^{-3}$



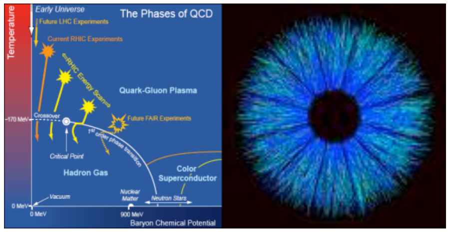
C
0
0.0002
0.0004
0.0006
0.0008
0.001
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2



×10^-3
C
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Δη

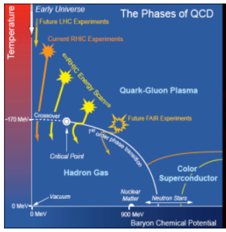


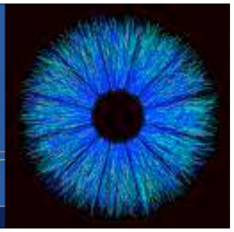
C
0.0000
0.0005
0.0010
0.0015
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
Δη



Centrality	Standard statistical errors	$E=\sqrt{\frac{\sum_{i=1}^{N} w_i R_i^2}{N\sum_{i=1}^{N} w_i}}$	$E=\sqrt{\frac{\sum_{i=1}^{N} w_i R_i^2}{\sum_{i=1}^{N} w_i}}$	RMS $\lvert\Delta\phi\rvert<1.0$ radians	RMS $-1.0<\Delta\phi<0.17$ radians
70-80%	0.542+0.021	0.542+0.003	0.542+0.02	0.5406	0.5449
60-70%	0.534+0.018	0.501+0.002	0.501+0.009	0.5505	0.5505
50-60%	0.504+0.088	0.519+0.002	0.519+0.012	0.5764	0.5753
40-50%	0.550+0.010	0.557+0.002	0.557+0.011	0.5941	0.5992
30-40%	0.664+0.019	0.667+0.003	0.667+0.016	0.6722	0.6230
20-30%	0.864+0.051	0.886+0.006	0.891+0.036	0.8452	0.7315
10-20%	1.003+0.117	1.043+0.011	1.043+0.064	0.9267	0.8480
5-10%	1.075+0.211	1.17+0.02	1.17+0.13	0.987	0.8899
0-5%	1.108+0.255	1.021+0.029	1.021+0.186	0.9449	0.8229

Shear Viscosity at RHIC





Schaefer & Teaney, Rept.Prog.Phys.72:126001,2009

fluid	P [Pa]	T [K]	η [Pa·s]	η/s [$\hbar/k_B$]
H_2O	$0.1 \cdot 10^6$	370	$2.9 \cdot 10^{-4}$	8.2
^{4}He	$0.1 \cdot 10^6$	2.0	$1.2 \cdot 10^{-6}$	1.9
QGP	$88 \cdot 10^{33}$	$2 \cdot 10^{12}$	$\leq 5 \cdot 10^{11}$	≤ 0.4

biggest

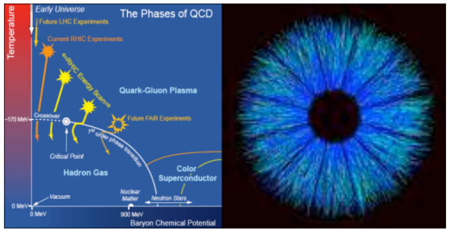
smallest

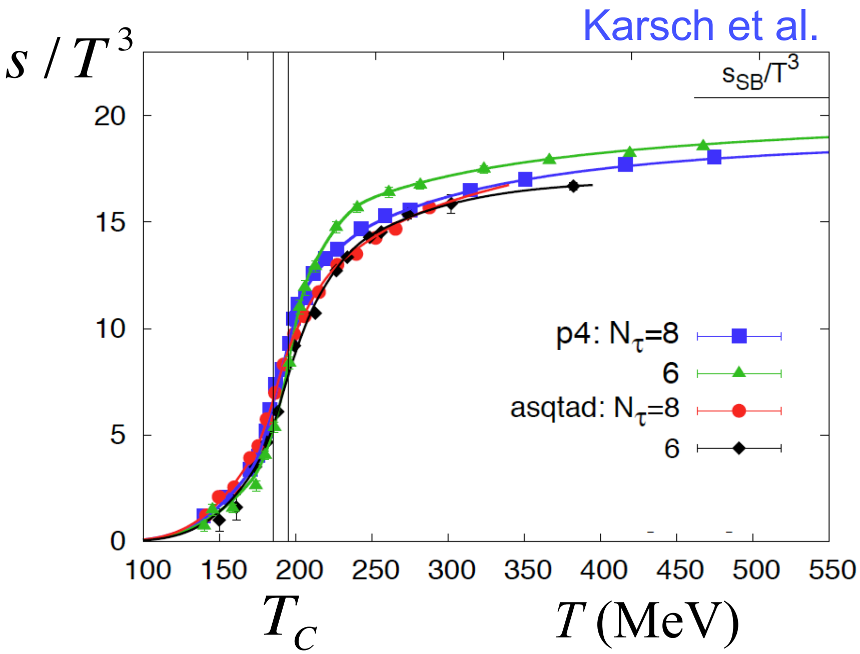
Dimensions:

entropy density s = density ($\rightarrow s/k_B$)

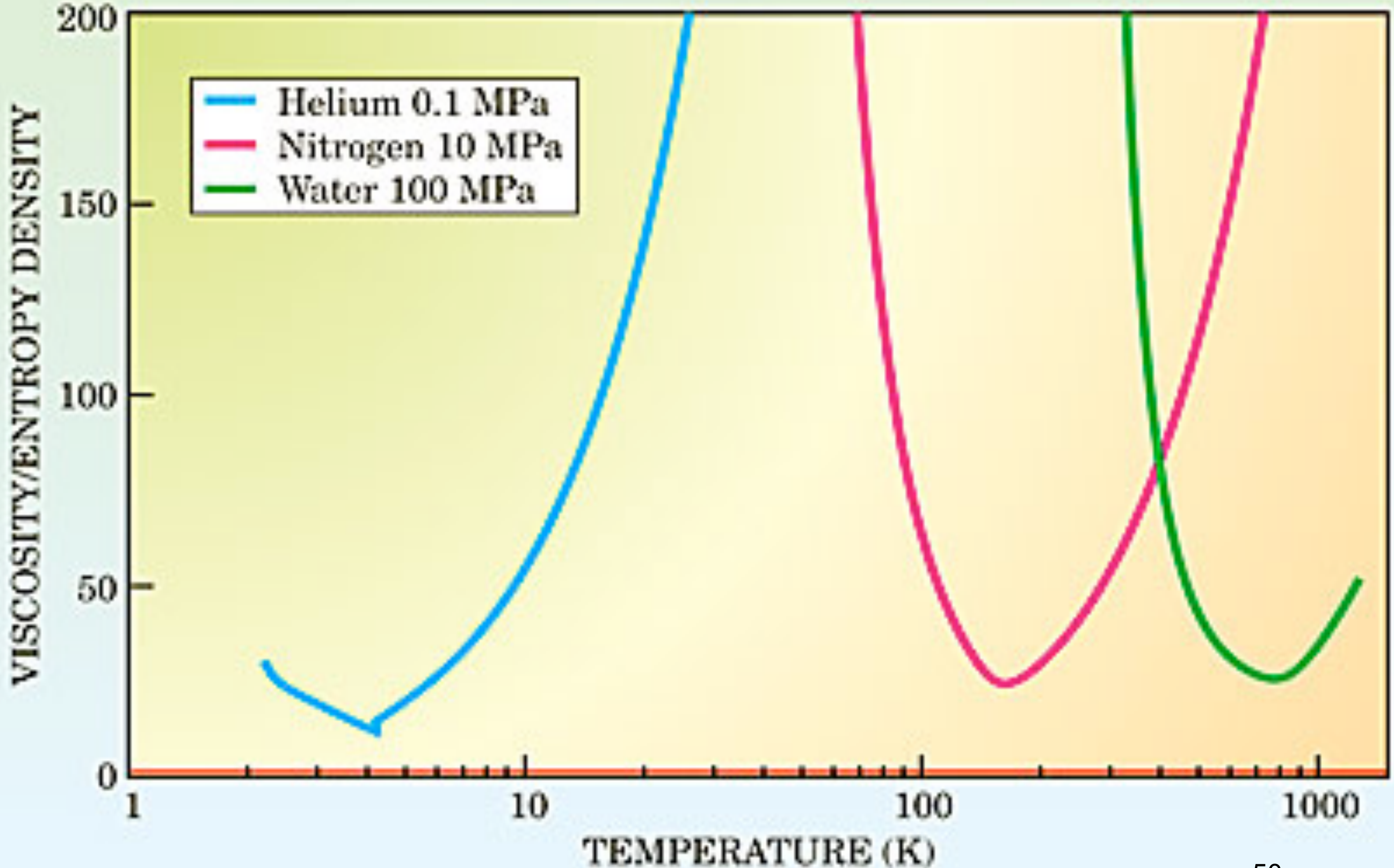
shear viscosity η = pressure $\times$ time = energy $\times$ density $\times$ time

η/s = energy $\times$ time = $\hbar \rightarrow 1$





Karsch et al.
s / T^3
s_{SB}/T^3
20
15
10
5
0
100
150
200
250
300
350
400
450
500
550
p4: N_τ=8
6
asqtad: N_τ=8
6
T_C
T (MeV)


Helium 0.1 MPa
Nitrogen 10 MPa
Water 100 MPa
VISCOSITY/ENTROPY DENSITY
200
150
100
50
0
1
10
100
1000
TEMPERATURE (K)